Early Journal Content on JSTOR, Free to Anyone in the World

This article is one of nearly 500,000 scholarly works digitized and made freely available to everyone in the world by JSTOR.

Known as the Early Journal Content, this set of works include research articles, news, letters, and other writings published in more than 200 of the oldest leading academic journals. The works date from the mid-seventeenth to the early twentieth centuries.

We encourage people to read and share the Early Journal Content openly and to tell others that this resource exists. People may post this content online or redistribute in any way for non-commercial purposes.

Read more about Early Journal Content at http://about.jstor.org/participate-jstor/individuals/early-journal-content.

JSTOR is a digital library of academic journals, books, and primary source objects. JSTOR helps people discover, use, and build upon a wide range of content through a powerful research and teaching platform, and preserves this content for future generations. JSTOR is part of ITHAKA, a not-for-profit organization that also includes Ithaka S+R and Portico. For more information about JSTOR, please contact support@jstor.org.

XX.

METASOMATIC DEVELOPMENT OF THE COPPER-BEARING ROCKS OF LAKE SUPERIOR.

By Raphael Pumpelly.

Presented Jan. 9, 1878.

Lake Superior is divided into two structurally distinct basins by the long peninsula of Keweenaw Point. The western basin lying between this point and the north-western shore of the lake is a geoclinal trough, bordered, and perhaps bottomed, by an immense development of volcanic rocks, in the form of great beds or flows. The south-eastern lip of this trough consists of these beds associated with conglomerates and sandstones, both of which consist essentially of porphyry detritus. These rocks, for which Major Brooks has proposed the name of the Keweenaw series, have a minimum actual thickness of more than two miles, and a linear extent, in Michigan and Wisconsin alone, of between two and three hundred miles. As a rule, they preserve a very marked uniformity of character throughout this area. Messrs. Foster and Whitney and Owen considered them as eruptions of the Potsdam epoch, basing their opinion chiefly on the external resemblance of the sandstones interbedded with the eruptive rocks to the closely adjacent Potsdam sandstone, and on a supposed conformability between the two series.

The State Survey, and the private surveys of Major Brooks and myself in Michigan, and later, in Wisconsin, those of Professor Irving, of the Wisconsin State Geological Survey, have discovered abundant evidence of non-conformability, and of the greater age of the Keweenaw series. This is, in fact, much more nearly conformable to the underlying highly tilted Huronian schists.*

They are thus the product of the earliest eruption of basaltic rocks to which a proximately definite age can be assigned. They were preceded by very extensive eruptions of acid rocks, especially porphyries.*

---

* Both these eruptive rocks and the sandstones have been referred to the Triassic period by C. T. Jackson, Jules Marcou, and R. Bell.

These basaltic rocks have been subjected to a wide-reaching alteration, which has produced marked changes in the internal condition of the beds, and has filled the fissures with a rich variety of minerals, whose constituents were derived from the products of this alteration.

In a previous article,† I sketched the relative ages of the minerals, especially those occurring in the veins.

In the present paper, I shall try to trace the changes that have taken place in the interior of the rock masses, in places where the only ingress and egress was through the capillary cracks formed by the cleavage and mutual boundary planes of the crystalline constituents.

The results at which I arrive are based on the study of several hundred thin sections, made by myself in order that I might study them before covering. The method followed was in general as follows: —

I. Examination of freshly broken surface under the microscope.

II. Measurement of the angles of crystals, generally cleavage angles, directly under the microscope, or with larger individuals on a reflecting goniometer.

III. Examination in detail of uncovered thin sections, trying hardness with the point of a delicate needle (which was also magnetized to detect magnetite) under any desired power up to a 4-10 objective.

IV. Etching the uncovered section, first with acetic acid to detect carbonates, then with muriatic acid.

V. Study of the covered section under the microscope, in transmitted and reflected light, and in polarized light.

VI. In many instances, qualitative chemical determinations, by my assistant, Mr. B. T. Putnam, were both necessary and decisive.

VII. A small series of analyses was made for me, by Mr. George W. Hawes and Mr. R. W. Woodward, in the laboratory of the Sheffield Scientific School.

---

* For recent discussions of the relative ages of the Silurian sandstone, the copper-bearing series, and the Huronian, the reader is referred to articles by Brooks and Pumpelly (Amer. Jour. Sci., vol. iii., 1874, p. 428); R. Irving (Amer. Jour. Sci., vol. viii., 1874, p. 46); T. B. Brooks (Amer. Jour. Sci., vol. xi., 1875, p. 210); and Reports of the Geological Survey of Canada.

† Paragenesis and Derivation of Copper and its Associates on L. Superior, Amer. Jour. of Sci., 3d ser., ii., 1871, p. 188; also, Geol. Survey of Mich., vol. i., part ii.

VIII. Whenever manageable crystals of feldspar could be got, they were cut parallel to the plane of easiest cleavage, and studied by Des Cloiseaux's method. A modification of Des Cloiseaux's method was used, to aid in determining the feldspar in thin sections of rock cut at random.

In the Report of the Geological Survey of Michigan, after a study based on the older lithological methods, I distributed the different varieties of these rocks under three heads; viz., coarse-grained and fine-grained melaphyres, and melaphyre porphyry. In the same volume, my assistant, the late Mr. Marvine, mistaking the augite for hornblende, described the coarser varieties as diorites, which was, at that time, a very common mistake.

In writing this paper, I had intended to retain my original classification; but, at the last moment, I received Rosenbusch's "Mikroscopische Physiographie der massigen Gesteine," in which the *plagioclase-augite* rocks are distributed in the following manner: —

I. PRE-TERTIARY.

1. *Granular.*
    - *a.* Plagioclase-augite = Diabase.
    - *b.* Plagioclase-augite-chrysolite = Chrysolitic diabase.
2. *Porphyritic;* containing more or less unindividualized base.
    - *a.* Plagioclase-augite = Diabase porphyrite.
    - *b.* Plagioclase-augite-chrysolite = Melaphyre.

II. TERTIARY AND POST-TERTIARY.

Granular or *Porphyritic.*
- *a.* Without chrysolite = Augite-andesite.
- *b.* With chrysolite = Basalt.

In thus designating as melaphyre only such rocks as are the older equivalents of those feldspar-augite basalts in which the original fluid magma is more or less represented by unindividualized base, it seems to me that Rosenbusch has simplified the troublesome problem involved in assigning to their proper places a large number of partially allied rocks.

The eruptive rocks of the Keweenaw series, or at least all those treated of in this paper, fall readily under the two heads of Diabase and Melaphyre.

The greater number of the beds are fine-grained diabase; coarse-grained diabase is much rarer; and intermediate between the two, as regards frequency of occurrence, is the melaphyre.

The fine-grained diabases are dark-brown, or gray, and green, with subconchoidal to irregular fracture, generally tough, but not hard, on account of the relative abundance of chlorite. Under the microscope, they are found to consist exclusively of triclinic feldspar, — sometimes associated with orthoclase, — and of augite and magnetite, and the alteration products of these minerals. They contain no chrysolite, nor any remnants of the fluid magma in the interstices between the constituents. The feldspar crystallized first, and the interstices were occupied by the augite and magnetite. The feldspar crystals are generally in square prisms, from a lengthening of the zone $O : i\breve{i}$.

The feldspar appears, from measurements, of the angle between the principal sections in alternating hemitropic bands by Des Cloiseaux's method, to be oligoclase in some instances, in some anorthite, and in others labradorite.

In some of the fine-grained varieties which occur more rarely, there is very little augite, and the rock has a light-gray color; this is notably the case with a great thickness of rocks on the Hungarian location, and to a much less degree with beds 45 and 66 of the Eagle River Section.

The coarse-grained varieties, with marked differences of external appearance as regards color and grain, have the same characters under the microscope as the finer grained, except that they contain much more numerous crystals of apatite, and that they often differ in regard to the secondary products.

The melaphyres are sharply marked. The constituents are plagioclase, augite, magnetite, chrysolite, and remnants of the fluid magma, occupying, in more or less small quantity, the interstices between the constituents. The chrysolite is generally more or less altered, and the remnants of the fluid magma are only rarely preserved in the form of glass base, for instance, in bed 90, Eagle River Section; it is almost always altered to a green chloritic substance. Beds Nos. 108 — "the Greenstone," — 90, and 64, all in the Eagle River Section, are types of the melaphyre, and to it belong, generally, what are locally known as mottled traps.

In the melaphyre, the feldspar appears to be generally anorthite, to judge from the size of the angles between the principal sections in alternating hemitropic bands in sections cut at random in the zone $O : i\bar{i}$. It is in sharply defined, long, narrow crystals, enclosed in the younger augite.

The melaphyre is less subject to the changes that produce the intermediate or amygdaloidal form, and is not so apt to have a true amygdaloid for the top of the bed.

FELDSPAR DETERMINATIONS.

	Measurements of the entering angle on the basal cleavage plane. (*Goniometer.*)			Angle between the principal sections adjacent hemitropic bands in sectio cut parallel to *O*. (Angle between maximum extinction (*Des Cloiseaux's Method.*)	
Lower zone of bed 22, Eagle R. Section					
Coarse-grained diabase, north of Delaware Mine					
Coarse-grained diabase, north of Delaware Mine, equiv. of bed 94					
Lower zone of bed 94, Eagle R. Section	Entering angle on basal cleavage	172° 50′ — 173° 12′	Alb. Olig.	Extinction Angle ± 3°	Olig
	Angle measured *O* | *i ĭ*	93° 24′	Alb Olig.		
	Same angle measured under microscope	93° 29′			
	Another crystal under microscope *O* | *i ĭ*	90° ± 10′	Orthoclase.		
Coarse-grained diabase, west of Quincy Mine					
Coarse-grained diabase, mouth of adit at the Dacotah Mine				Ext'n. angle, two-thirds is on one side in each instance 23° 43°	Ano
Bed 96, Eagle R. Section; diabase. Feldspar prehnitized	Entering angle	172° 09′ — 172° 49′	Alb Olig or Labr.	Angle between line of ext'n. and edge *O* | *i ĭ* . 6° & 0° In other sets of bands 6° and 3°	Lab
Bed 98, Eagle R. Section; diabase. Feldspar prehnitized				Extinction angle all in *one set* of bands 6°	Lab
Bed 107 A, Eagle R. Section (light type), diabase. Feldspar prehnitized		171° 30′ — 172° 21′	Anor. Olig.		
So-called Syenite. Granite St. Quarry, Somerville, Mass.: locality known for its prehnite. Feldspar much altered to prehnite				Extinction angle 5° 54′ to 8°. Sect. oblique. Angle in one set 2 to 3 times as large as in other	Alb.
Lower zone of bed 87, Eagle R. Section. Diabase		171° 26′ — 172° 33′	Olig. Alb.		
Middle " " " " " "					
Bed 45, " " "					
Lower zone of bed 66, " " "					
Fine-grained, hard diabase, Southside location					
Bed 106, Feldspar segregation. Diabase		170° 54′ — 171° 06′	Anorth.	13° 30′ — 16°	Labr
Bed 107 B., (dark type), Eagle R. Section. Diabase					
Lower zone of bed 108, Eagle R. Section. "The Greenstone." Melaphyre		171° 58′ — 172° 25′	Anor. Olig.		
Bed 90, Eagle River Section. Melaphyre					
Bed 64, (lower zone), Eagle R. Section. Melaphyre					
Bed 65, under the "ash bed," Eagle R. Section. Diabase or diab. porphyry					
8th Bed, west of Pewabic, west conglomerate, St. Mary's location. Diabase or diab. porphyry					
Bed 95, Eagle River Section. Diabase				10° — 17° and 13°	Labr
Light-colored diabase, "800 ft. E. of Hungarian Lode"					
Bed 61 (lower zone), Eagle R. Section. Analcitic.					
Diabase near Houghton ("y. bowld.") Feldspar, changed to prehnite and chlorite					
Coarse-grained rock from Sec. 5, T. 47, R. 46, Mich.		171° 41′ — 171° 46′	Anorth.	7°	
Pseudo-amygdaloid, 50 ft. west of Houghton conglomerate. Mesnard location					

* Very unequal. † In the rock. ‡ In the rock. Whitney Geol. L. Supe

FELDSPAR DETERMINATIONS.

s of the entering angle on the al cleavage plane. (*Goniometer.*)			Angle between the principal sections of adjacent hemitropic bands in sections cut parallel to *O*. (Angle between maximum extinctions.) (*Des Cloiseaux's Method.*)		Angle between the principal sections of adjacent hemitropic bands in sections cut at random in the zone *O : i ĭ*. (*Des Cloiseaux's Method.*)		Specific gravity of the Rock.	Probable feldspar.
. . .	. . .	. . .	. . .	. . .	34° 34° 36° 51° 60° 62° . . .	Labr.	. . .	Labradorite.
. . .	. . .	. . .	. . .	. . .	**22°** **30°** 41° **47°** 50° 60° 71° .	Anorth.	. . .	Anorthite.
. . .	. . .	. . .	. . .	. . .	22° **23°** 31° 33° **33°** 33° 36° .	Olig. or Lab.	. . .	Oligoclase.
al cleav- . . .	172° 50′ — 173° 12′	Alb. Olig.	Extinction Angle ± 3°	Olig. And.	29° **30°** **31°** 31° 34° 37° 38° 41°	Olig. or Lab	2.94	Oligoclase.
ĭ . . .	93° 24′	Alb Olig.	. . .	. . .	. . .	. . .	. . .	
under . . .	93° 29′	. . .	. . .	. . .	. . .	. . .	. . .	
micro- . . .	90° ± 10′	Orthoclase.	. . .	. . .	. . .	. . .	. . .	Orthoclase.
. . .	. . .	. . .	. . .	. . .	43° 46° 48° 49° 55°	Lab. or Ano.	. . .	Lab. or Anorth.
. . .	. . .	. . .	Ext'n. angle, two-thirds is on one side in each instance . . . . . . 23° 43°	Anorth.	59° 62° 63° 66° 66° 78° . . .	Anorth.	. . .	Anorthite.
. . .	172° 09′ — 172° 49′	Alb Olig or Labr.	Angle between line of ext'n. and edge *O* | *i ĭ* . 6° & 0° In other sets of bands 6° and 3° .	Lab. Alb. . . .	6° 7° 11° 13° 31° 45° 58° 20° 20° 27°	Lab. Anor.	2.90	Labradorite.
. . .	. . .	. . .	Extinction angle all in *one set* of bands . . . 6° . .	Lab. Alb.	16° 20° 41°	Lab. . . .	. . .	Labradorite.
. . .	171° 30′ — 172° 21′	Anor. Olig.	. . .	. . .	10° 11° 24° 29° 39° 56° 57° 60°	Lab. Anor.	Rock 3.03 Feldsp. 2.73 Aug. 3.39	Labradorite.
. . .	. . .	. . .	Extinction angle 5° 54′ to 8°. . Sect. oblique. Angle in one set 2 to 3 times as large as in other	Alb. Olig.	24° 26° 31° 32°	Alb. Olig. .	. . .	Alb. or Olig.
. . .	171° 26′ — 172° 33′	Olig. Alb.	. . .	. . .	22° 23° 34° 36°	Alb Olig.	2.6–2.73 too low for Labradorite.	Alb. or Olig SiO^2 46.32 %.†
. . .	. . .	. . .	. . .	. . .	**26°** **29°** 34° 35° **36°** 36° . .	Alb. or Olig.	2.73–2.75	Alb. or Olig.
. . .	. . .	. . .	. . .	. . .	21° 21° 24° 28° 31° 34°. . .	Alb. or Olig.	2.91	Alb. or Olig.
. . .	. . .	. . .	. . .	. . .	**5°** **15°** **15°** 28° **31°** 35° . .	Alb. or Olig.	2.93	Alb. or Olig.
. . .	. . .	. . .	. . .	. . .	61° 66° **66°** 68° 70°	Anorth. . .	. . .	Anorthite.
. . .	170° 54′ — 171° 06′	Anorth.	13° 30′ — 16°	Labr. . .	**11°** 12° 18° 29° 31° 62° **64°** .	Lab. An. .	. . .	Labradorite.
. . .	. . .	. . .	. . .	. . .	**16°** **20°** 30° 49° 60° 70° **75°** .	Anorth. . .	. . .	Anorthite.
. . .	171° 58′ — 172° 25′	Anor. Olig.	. . .	. . .	43° **43°** **48°** 49° **50°** 55° 58° **60°** **60°** 63° 69° 70°	Anorth. . .	2.95	SiO^2 50.20 %.‡ Anorthite.
. . .	. . .	. . .	. . .	. . .	**38°** 49° 57° **60°** 62° **66°** . .	An. Lab. .	2.89	Anorthite.
. . .	. . .	. . .	. . .	. . .	**47°** 64° 67° 73° **74°**	Anorth. . .	2 65–2 70	Anorthite.
. . .	. . .	. . .	. . .	. . .	**38°** 55° **60°**	Lab. or An.	2.98	Lab. or Anorth.
. . .	. . .	. . .	. . .	. . .	**47°** **48°** **49°**	Lab. or An.	. . .	Lab. or Anorth.
. . .	. . .	. . .	10° — 17° and 13°	Labr. . .	39° **50°** **51°** 51°	Lab. An. .	. . .	Labradorite.
. . .	. . .	. . .	. . .	. . .	* **25°** **27°** 34° **36°**	Alb. Olig. .	. . .	Alb. or Olig.
. . .	. . .	. . .	. . .	. . .	31° 43° 64° **66°**	Lab. An. .	. . .	Lab. or Anorth.
. . .	. . .	. . .	. . .	. . .	10° 19° 19° 20° 23° 23° 27° 28° 28° 29° . . .	Alb. or Ol. .	. . .	Alb. or Olig.
. . .	171° 41′ — 171° 46′	Anorth	7°	. . .	10° **17°** 27° **42°** **43°** 48° **62°** 65°	Lab. An. .	. . .	Labradorite.
. . .	. . .	. . .	. . .	. . .	44° **61°** **64°** 77°	. . .	. . .	Anorthite.

y unequal. † In the rock. ‡ In the rock. Whitney Geol. L. Superior.

Not a trace of hornblende was observed in any of these rocks; it occurs with orthoclase in some related coarser-grained rocks of the Keweenaw series near the Wisconsin State line.

The almost general acceptance of Tschermak's theory, which breaks down the boundaries between the triclinic feldspars, has rendered the determination of these a matter of wholly secondary importance in diagnosis.

But the feldspar plays such an important part in the series of changes that have taken place in these rocks, that it seemed desirable to determine its position in the plagioclase series. This is no easy task. Except in a few instances, chemical analysis must necessarily fail, because the rocks have generally changed in character, — either the feldspar or augite being more or less altered; the composition of the augite is an unknown quantity; and isolated crystals of both minerals are too small to be got out clean for analysis. The analyses I had made were of little use in determining the feldspar. The entering angle on the basal cleavage seemed to offer a ready means of determination by direct measurement. I therefore made a long series of careful measurements with a reflecting goniometer, with very unsatisfactory results; for the cleavage surface in one or both sets of hemitropic individuals is apt to be either curved or crossed by innumerable smaller striae, each giving an image, so that the result lies between extremes often from thirty minutes to one degree apart, or more than the difference between albite, oligoclase, and labradorite, and in addition to this, different authorities give different measurements for this angle. Still I give the results in the general table.

Des Cloiseaux's beautiful method is much more promising. This consists in cutting very thin sections parallel to the basal cleavage, and measuring, between crossed nicols, the angle between the edge $O \mid i\breve{i}$. and the principal section — maximum extinction of light, — or between the maximums extinction in the alternating hemitropic bands to guard against errors that might arise from obliquity in the section. Des Cloiseaux determined this double angle, from many measurements, to be: —

Oligoclase	0° — 2°
Andesine	3° — 4°
Albite	7° 40′ — 9° 40′
Labradorite	10° 34′ — 13° 56′
Anorthite	40° — 80°
Microcline	30° 54′

Aside from the fact that it is very rare to find a crystal in these rocks large enough to manage in cutting: *i. e.*, not less than $\frac{1}{20}$ inch square, there was the possibility that these might be different from the dominant feldspar of the rock. The results obtained by this method are given in the table.

It occurred to me that this method might be modified by determining the range of this angle in the zone *O: iī*, and measuring the angle between extinctions in several individuals in a section, always taking care that the angles should be equal or nearly so in both bands.

The following is a proximate determination of the range of the angle included between the principal sections of the alternating bands in the zone *O: iĭ* for the different feldspars. These values are based on the position of the optic-axial plane and of the bisectrix, as established by Des Cloiseaux.

	Minimum.	Sections cut parallel to *O*.	Maximum in the zone *O i ī*.	Between line of extinction and edge *O*|*i ĭ* sections parallel *i ĭ*.
Orthoclase	0°	0°	0°	4° — 5°
Albite	0°	7° 30′ — 10°	32° — 34°	15° — 20°
Oligoclase and Andesine . .	0°	0° — 4°	36°	0° — 7°
Labradorite	0°	10° — 14°	62°	20° — 27°
Anorthite	0°	Sections in *i ī*. 20° — 26°	Sections in *O*. 40° — 80°	33° — 46°

From this table, the angle in question appears to stand in an inverse relation to the acidity. By measuring a considerable number of twins in a thin section, taking care to select only such as form equal angles on the opposite sides of the cross hair, it is often possible to distinguish anorthite and labradorite, but it is scarcely practicable to discriminate between albite and oligoclase by this method alone.

In giving the result of these measurements in the general table, I have given the amount of the double angle, and have put down only those measurements in which the angles in the two members of a twin were even, or very nearly so. Where the angle was ½ or ⅙ greater in one member than in the other, the result is given in italics.

This is the only method that could be used in these rocks, which are generally too much altered to admit of a calculation of the mineral constitution from chemical analyses; and the feldspars are apt to be so much affected that the tests for fusibility, and by etching with acid, are useless. But the smallest unaltered portions of a crystal answer readily to the optical tests, especially if the section is cut thin. By using a circular polarizing quartz plate 3.75 millimetres thick, as recommended by Klein and Rosenbusch, inserted just above the objective, and by turning the analyzer till a violet tint is obtained, the readings can be made with much greater precision than by observing the maximum of darkness. In the presence of the quartz plate, all the double-refracting portions of the section appear in different colors, excepting where a principal section coincides with a nicol plane; crystals so placed will be violet, and a very slight disturbance will change the color to blue or red.

The chief defect in this method is in the fact that, used alone, it detects only the feldspar that gives the highest angle, while there may be two kinds present.

The coarse-grained varieties differ very markedly in external appearance. There are several varieties, some of which are common to the most distant portions of the copper district; they are marked by difference in grain, texture, and color, and in the nature of their secondary constituents. This last difference is apparently largely due to variation in the feldspars. The coarser forms have more or less orthoclase, and in some this may predominate. The triclinic feldspar varies in character from oligoclase to anorthite.

The pyroxene is to all appearances the same augitic variety in all, and in all instances it crystallized after the feldspars and occupies the interstices between these. Only in rare instances — as in bed No. 95, Eagle River Section — a well-defined cleavage seems to mark the pyroxene as diallage.

The specific gravity varies from 2.89 to 3.03; the colors from dark-brownish black, with resinous lustre, as in bed No. 95, to a very light gray, as in bed No. 107. Between these extremes, there are varieties of many shades of green and brown, or red. Indeed, specimens of the eight or ten varieties differ so widely in external appearance, that it is difficult to believe that they are closely allied to each other, and to the finer-textured rocks, until we see the similarity of constitution and texture as regards primary constituents, and also their similar mode of occurrence, and the fact that they are interbedded with the finer-grained diabase. Such of these coarser forms as exhibit interesting phases of alteration will be described. I will remark here that Mr. Marvine, in his otherwise very excellent description of the beds of the Eagle River Section (Geol. of Mich., vol. i. part 2, pp. 119-

140), wrongly designated these coarser rocks as diorites. I refer the reader to these very faithful descriptions, by Mr. Marvine, of the external characteristics of these rocks, adding only the caution that, wherever he mentions hornblende, it should read augite.

As it is the object of this paper to describe the internal changes that have taken place in these rocks, rather than a description of the rocks themselves, the sequence in which they are described is that which is best adapted to the immediate purpose.

EARLIEST CHANGES IN MELAPHYRE.

"*The Greenstone.*" The rock, commonly known in the copper district as "the greenstone," is the best type of this subdivision. Forming a bed 400–500 feet thick, dipping northerly, its outcrop consists of a continuous series of ridges and nearly vertical escarpments, often several hundred feet high. These extend from the Allouez mine to Point Keweenaw, and form both the most salient topographical feature of the peninsula, and a well-defined horizon, to which the geologist and the miner refer their measurements. The rock has suffered only to the extent of a partial alteration of one of its constituents, — the olivine.

It is dark-green, greenish-black, finely crystalline, very compact, hard, and brittle, and breaks with an uneven to semi-conchoidal fracture. Porphyritic crystals, apparently of orthoclase, from ⅓ inch in length down, occur here and there, — one or two on the surface of a specimen. They are generally single individuals; but sometimes twinned after the Carlsbad law, as is shown by the oppositely inclined basal cleavage. The powder of the rock yields to the magnet a beard of magnetite. The specific gravity is 2.92–2.95. It is an important characteristic of this rock, that its freshly fractured surface is mainly occupied by spots ⅓ to ¾ inch in diameter, each of which reflects the light with a satin-like sheen. The reflection is not carried to the eye from all the spots at once: it is generally necessary to change the position of the specimen many times to observe the different reflections. Aside from this sheen, there is nothing, either in difference of color or texture, visible to the naked eye, to betray the presence of these spots, which might be called lustre-mottlings.

To the naked eye, this phenomenon suggests, at once, interrupted cleavage of large individuals of one of the constituents, as the cause; but, under a strong hand-glass, these reflecting surfaces show the same granular texture and character as the rest of the rock; and it is only when examined under the microscope, with an objective of low power and in polarized light, that the appearance to the unaided eye is corroborated. We here find the cause in the fact that each spot is the cross-fracture or cleavage of a crystal of pyroxene, which in crystallizing has enclosed hundreds of feldspar crystals.

The weathered surface is rusty gray, scarcely $\frac{1}{50}$ inch thick; but it is covered with knobs which are due to the more rapid destruction of the materials between the pyroxene individuals.

Examining thin sections under the microscope, we find the constituents to be *plagioclase*, *pyroxene*, *olivine*, and its alteration product, as well as magnetite, and an unindividualized substance, both fresh and altered, occupying interstices.

In thin sections, the plagioclase is seen to exist in very sharply defined and fresh, thin, tabular crystals, .001 to .002 inch thick, and .01 inch, and less, long. It contains scattering interpositions of an opaque black substance, and minute brown particles, which may be, or have been, glass.

The crystals of plagioclase have predetermined the contours of all the other constituents, except the olivine, which crystallized first.

The predominating feldspar is anorthite, as determined by the angle between the principal sections in adjoining bands in the zone *O : iī*. Scattering large crystals, which happen in the sections to be cut parallel to *i.ĭ.*, have their principal sections at an angle of 23° with the edge *O : iĭ*, which would indicate albite or labradorite.

The augite is very fresh and transparent, almost colorless in the thin section, but with a tendency to purple-gray. An imperfect cleavage is indicated by somewhat irregular parallel fractures. It fills the interstices between the closely packed individuals of feldspar in such a manner that a single pyroxenic crystal encloses many hundreds of these, while its crystalline integrity is shown by the uniform color in polarized light, and by the arrangement of the cleavage cracks throughout the area of the augite individual.

It is a remarkable fact that, while these large individuals of pyroxene contain thousands of feldspar crystals, they enclose only very few of olivine or of magnetite. These minerals, together with the unindividualized substance, are crowded into the spaces between the pyroxenes. In this intermediate space, which surrounds the pyroxene individuals with a continuous network, we find, also, a few small pyroxenes, just as isolated grains of olivine occur in the pyroxene areas.

A careful examination of this occurrence will, I think, convince the observer that, at the time the pyroxene crystallized, both the olivine and the feldspar crystals, and apparently the magnetite, were already individualized; for, where we find any of these in contact with the pyroxene, we see that the latter has adapted itself to the already defined contours of the others. While the pyroxene enclosed the feldspar crystals with ease, it crowded the other constituents almost wholly into the surrounding spaces; a process which was facilitated by the presence of the then fluid, unindividualized substance.

The pyroxene contains, also, brown interpositions, similar to those in the feldspar, and some opacite; and, where it occurs with olivine, it often surrounds the grains of this mineral.

The magnetite bodies are of irregular shape, moulding themselves sharply around the contours of the feldspar and olivine. Their sharply defined outlines are black and fresh.

The olivine is abundant in integral and aggregated grains, and, very rarely, in crystals with recognizable though rounded contours. The individuals are .0008 to .005 inch in diameter, and are readily distinguishable from the augite, between crossed nicols, by the difference of colors, and in the crystals, by the parallelism of the principal section with the longer sides. Where pains have been taken to give a tolerably good polish to the surfaces of the thin section, the characteristic finely pitted surface of the olivine distinguishes it, even in ordinary light, from the augite, which takes a more perfect surface.

There are few grains of olivine in this rock that are not more or less altered to a very pale green substance, sometimes tinged with brown. Under a high power, the olivine is seen to be traversed by intercommunicating canals .0002 to .00005 inch thick, filled with a clear, faint yellowish green to greenish-blue substance. From the sides of these channels, jagged points of the same substance penetrate the fresh olivine. In this manner, larger or smaller parts of the grains have been changed to a feebly double-refracting substance which gives an aggregate polarization due to the arrangement of the minute individuals of the alteration product, which are sometimes felted, at others, parallel fibrous. This product is dichroitic; pale green when the fibrous structure is parallel to the shorter diagonal of the polarizer, and pale orange when parallel to the longer diagonal. On the uncovered sections, this alteration product was found to be very soft under the needle.

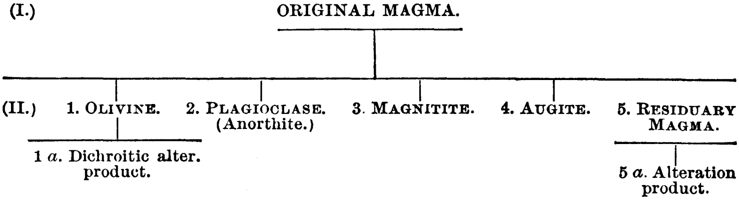
Apparently, not more than twenty to thirty per cent. of the olivine is altered, which is very remarkable in a rock of such great age, considering the fact, which is emphasized by Zirkel,* that the olivine is subject to complete alteration, even when its neighbors remain wholly intact.

---

* Mikrosc. Besch. d. Mineralien u. Gesteine, p. 217.

Where the interstices between the constituent crystalline minerals are not occupied by augite, they are filled with a transparent substance, in places colorless, in others of faintest green, almost colorless, only just distinguishable from the colorless feldspar in ordinary transmitted light. It often penetrates the feldspar crystals in cross fractures. Between crossed nicols it is black, sprinkled with minute blue-gray clouds, — an aggregate polarization due, probably, to either an exceedingly minute radiating fibrous, or a granular, structure. Under a $\frac{1}{16}$ inch objective (Hartnack's, No. 10), portions of the black seem to remain dark on revolving between crossed nicols. The substance is at the most only very feebly double refracting. Unfortunately I was able to find with a low power, and to try with the needle on an uncovered section, only those portions which were faintly green, and these were soft. Still, I am forced to believe that we have here to do with remnants of glass base, which is altered in the faint green portions to a chloritic or serpentine substance. Its whole mode of occurrence in this very fresh rock shows conclusively that it is not an alteration product of any of the constituent crystalline minerals.

The relative ages of the constituents of this rock appear to be well defined as follows: —


(I.)
ORIGINAL MAGMA.
(II.)
1. OLIVINE.
2. PLAGIOCLASE. (Anorthite.)
3. MAGNITITE.
4. AUGITE.
5. RESIDUARY MAGMA.
1 *a*. Dichroitic alter. product.
5 *a*. Alteration product.

The residuary magma (5) must have been the last to solidify; to its presence was due the internal mobility of the mass, which rendered it possible for the augite to crystallize in larger individuals, and, in doing so, to crowd from its centres the olivine and magnetite individuals.

This residuary base, probably, differs in chemical constitution from the original magma, since it is only the residue of this after the removal of the ingredients forming the crystalline constituents.

Highly altered Melaphyre. — While the type represented by "the greenstone" is one of the most constantly recurring varieties throughout the copper district, it is very rarely in as unaltered a condition, and it is usually finer grained and almost aphanitic in texture. Where it is least altered, the fresh fracture has less lustre, but the characteristic lustre-mottlings are present to the same extent, though in smaller spots.

An instance of a highly altered form of this variety occurs at the shaft on Mabb's vein near Houghton. The specimens are from the immediate neighborhood of the fissure vein; and the one on which the following observations were made represents the contact: —

It is about 5 × 4 inches, and carries at one end $\frac{3}{4}$ of an inch thickness of the vein, in the form of a parallel arrangement of calcite-quartz seams, separated by thin chlorite layers.

In close connection with this altered form there is an intermediate stage which has an uneven fracture, and is distinguishable from the "greenstone" only by a somewhat finer texture, and the smaller size of the lustre-mottlings. The magnet extracts a little magnetite from the powder. In thin sections, the characteristic structure to which the lustre-mottlings are due appears at once between crossed nicols, and the same crowding of olivine and magnetite individuals into the space surrounding the large pyroxene areas. Both the feldspar and pyroxene appear to have suffered but little from alteration; but the chrysolite individuals are all altered, and the unindividualized substance is changed to a green non-dichroitic substance.

The more altered form has an even to semi-conchoidal fracture. The freshly broken surface is formed of nearly round, green spots, about $\frac{1}{4}$ inch in diameter, in a connected network of brown.

Fragments of the rock effervesce strongly in muriatic acid. Its powder does not yield magnetite.

The structure that in the less-affected rock causes simply lustre-mottling is, in this altered form, marked by a decided color-mottling.

In thin sections, the plagioclase crystals show still, to a great extent, the twin striation in polarized light.

The olivine individuals are changed to a slightly yellowish green substance with brown stained cracks, and with the outer portion also stained brown. They are very soft under the needle.

Examining these with a strong glass, on a fresh fracture of the rock, they show a well-marked cleavage in one direction, — an irregular fracture in all others, — and have a dark red color with somewhat wax-like lustre. They blacken before the blowpipe, and fuse with difficulty on the edges of very small fragments.

In the thin sections, many of the individuals are so stained, in part or throughout, by oxide of iron as to be wholly opaque; but by etching with muriatic acid, the discoloration is removed. The staining is, therefore, probably due to a deposition of the oxide in the cleavage planes.

Under the microscope, the cleavage is very evident in many individuals, but it is more marked in the less altered rock. In those instances where the cleavage is well defined, an examination with one nicol show decided absorption, — the substance being almost colorless when the cleavage lines coincide with the longer diagonal of the nicol, and delicate green when perpendicular to this.

Between crossed nicols, darkness occurs when the cleavage lines coincide with a nicol-plane; and some individuals which show no cleavage lines remain dark during a revolution.

This should seem to indicate that the substance is uniaxial.

Many of these grains, especially in the more altered rock, differ from the above in that they show an aggregate polarization due to a confused fibrous or felted structure.

The pyroxene in the more altered rock is apparently wholly changed to an impellucid white substance, which, between crossed nicols under a high power, shows a brilliantly variegated aggregate polarization, an irregular damask arrangement of bright-colored lines, forming concentric circles or parallel wave-like lines. This substance is not confined wholly to the pyroxene: it occurs also in the form of irregular veins which have a rough tendency to parallelism, and no defined walls but which extend through the feldspar crystals as well as through the other constituents.

One of the specimens of this rock has at one end fragments of the Mabb's vein in the shape of five or six lenticular layers of calcite, with quartz $\frac{1}{16}$ — $\frac{1}{8}$ inch thick, separated by still thinner layers of the rock. A close examination of the specimen near this portion reveals the presence of very minute veinlets of calcite parallel to these larger ones, while a still closer observation of the weathered surface shows that still finer parallel veinlets occur throughout the specimen.

Under the microscope it became evident that some of the veinlets contained quartz as well as the calcite.

On etching a thin section with acetic acid under the microscope, the removal of the calcite was observed, and it became evident that the irregular veins of impellucid white substance (which I mentioned as extending beyond the pyroxene crystals) followed these veinlets, the calcite forming the median line of the impellucid veins. The acetic acid removed the calcite through to the under side of the section, but the impellucid substance remained; nor was it appreciably changed by treatment during twenty-four hours with cold muriatic acid, which removed considerable iron from the altered chrysolite.

On etching thin sections with acetic acid, during a period of forty-eight hours, it was found that not only was calcite removed from the impellucid veinlets, but also extensively from the representatives of the pyroxene. The action of the acid revealed the presence of numerous cracks in the latter, which were filled with a colorless, more or less transparent, and double-refracting substance not acted upon by the acid. On examining the etched section by reflected light, and afterwards in polarized light, the former positions of the pyroxene individuals were found to be occupied by a thoroughly honeycombed mass; the crystalline substance that had been formed in the cracks now forming the partitions between cells, which contained an apparently confused granular mass of white translucent substance. On the thinner edges of the section the cells were often entirely empty, perhaps owing to mechanical action in washing after etching.

The plagioclase remained, as before the treatment with acid, apparently fresh, except in immediate contact with the calcite veinlets, and also where former interpositions of glass base had been changed to a greenish double-refracting substance.

That the ferric oxide which stains the pseudomorphs after chrysolite, and also occupies capillary cracks in other constituents, was formed from the iron in the chrysolite, seems to be apparent from the fact that it exists in the less altered form of the rock where the pyroxene is perfectly fresh.

That this staining is older than the calcite appears from the fact that the calcite veinlets cut the stained cracks, and are never themselves discolored. But the magnetite appears to have been oxidized at a later date without spreading a discolorization.

The chrysolite was the first to suffer, for we find it wholly changed in the less altered form of the rock. The change, possibly, consisted in a hydration, accompanied by separation of iron.

There occur seams $\frac{1}{100}$ inch thick of a green, non-dichroitic chlorite, which shows lamellar aggregate polarization. These seams are traversed by the calcite veinlets, and are, therefore, older.

The quartz, both in the larger vein fragment and in the veinlets, seems to be younger than the calcite, though the evidence is not as positive as could be wished. In a section cut from the vein fragment, I observed a quartz crystal cut nearly perpendicular to the principal axis, and surrounded by calcite: it seems that the growth of the quartz was interfered with; for its development is marked by successive concentric layers, and while the central ones are complete there was evidently not room for the outer layers on one side, owing to the proximity of the face of a calcite crystal against which they end abruptly.

In some instances, the quartz shows a comby structure, and the interstices between the opposing ends — the median line — are occupied by a little green, chloritic substance.

The process of growth of the small veins near the fissure vein is well defined under the microscope. Throughout the body of the specimen, the calcite is confined to the pseudomorphs after pyroxene, and to the minute crooked veinlets. But near the end bearing the vein fragment, a greater regularity in the form of the minute veins is apparent, and is evidently due to the lesser resistance offered in the direction of the fissure. The veinlets unite, to form wider veins; and in doing this the tributary always enters between the larger veinlet and the rock, and maintains this position. Each member of the compound vein is marked by its independent crystallization, and by the narrow borders of impellucid substance, and the whole appearance is best comparable to the map of a glacier which has received several tributaries, each marked by its lateral moraines.

The greater facility for drainage indicated in this structure has had for effect, near the vein, the removal of the calcite from the pseudomorphs after pyroxene, which appear now to be filled with chlorite and quartz.

Minute particles of native copper occur in these veinlets. An examination of fragments containing the copper flakes, under the microscope in reflected light, showed the metal to be younger than the quartz, for it adapts itself to the contours and cracks of the latter.

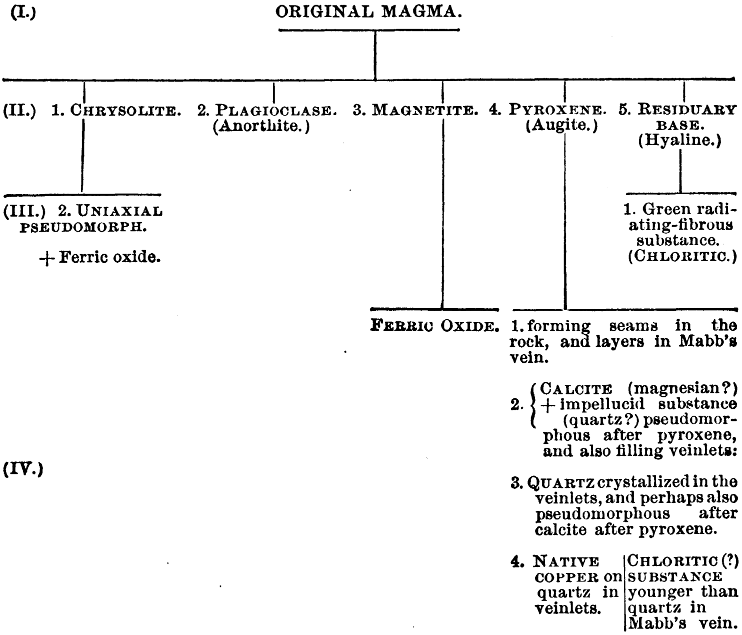
Throughout all this change the plagioclase appears to have suffered little, except in the immediate contact with the fissure vein, where it has lost in most individuals the evidence of twinning in polarized light. It is also, perhaps, affected in the immediate contact of its crystals with the veinlets, but it is generally so fresh that it cannot have contributed appreciably to the changes that the rock has undergone.

The first change — that affecting the chrysolite and the residuary base — may have been simply of the nature of a hydration of these, accompanied, in the former, by a separation and oxidation of the iron. This represents the condition of the "greenstone," in which this change is partially accomplished, and of the similar "mottled traps" throughout the copper district, in which the alteration of the chrysolite and residuary base is, probably, generally complete.

The next change has affected the magnetite, and still more the pyroxene, the destruction of which has given birth to, at least, three products; namely, *chlorite*, *calcite*, and *quartz*. The relative ages of these, as expressed in the accompanying paragenetic table, are as observed where they are all represented in the veinlets. In the breaking up of the pyroxene combination, the iron, alumina, and magnesia, and part of the silica were removed, and went to form chlorite; the lime, combined with the foreign carbonic acid, — possibly, also, with some magnesia, — remained as a pseudomorph: there is less positive evidence that the substance occupying cracks in these pseudomorphs (and which is not affected by a twenty-four hours' treatment with cold muriatic acid) is quartz, and that it is pseudomorphous after calcite.

The only remark to be made with regard to the native copper is that it was observed only in the veinlets near the fissure vein, and as being younger than the quartz.

The paragenetic scheme for this rock should seem to be as follows: —


(I.)
ORIGINAL MAGMA.
(II.)
1. CHRYSOLITE.
2. PLAGIOCLASE. (Anorthite.)
3. MAGNETITE.
4. PYROXENE. (Augite.)
5. RESIDUARY BASE. (Hyaline.)
(III.)
2. UNIAXIAL PSEUDOMORPH.
+ Ferric oxide.
1. Green radiating-fibrous substance. (CHLORITIC.)
FERRIC OXIDE.
1. forming seams in the rock, and layers in Mabb's vein.
(IV.)
2. CALCITE (magnesian?) + impellucid substance (quartz?) pseudomorphous after pyroxene, and also filling veinlets:
3. QUARTZ crystallized in the veinlets, and perhaps also pseudomorphous after calcite after pyroxene.
4. NATIVE COPPER on quartz in veinlets.
CHLORITIC (?) SUBSTANCE younger than quartz in Mabb's vein.

CHANGES IN THE LOWER PARTS OF THE BEDS.

There is no variety of these rocks that has not undergone a greater or less change. The least altered instance is that which forms the "Greenstone range," in which the remnants of magma-base and part of the chrysolite have been changed, while a considerable portion of the chrysolite, and all of the plagioclase, pyroxene, and magnetite, remain apparently quite intact. The further change which this variety has undergone under favorable circumstances, namely, the close proximity of a vein, has been already described. I propose now to consider the evidence, and, so far as I have been able to trace it, the progress, of the alteration which has taken place in the body of the rock, especially in the diabase proper, away from the influence of veins, and where the influx into, and drainage from, a given point, could have taken place only through capillary cracks and the cleavage planes of the crystals. As I have shown elsewhere, all the beds have very sharply defined hanging walls and foot-walls, while between these limits the rock has, generally, three subdivisions; namely, a lower — least altered zone — below, a pseudoamygdaloid in the middle, and amygdaloid at the top. The upper one, and sometimes the middle one, are, in places, wanting. The relative thickness of these subdivisions is very variable, not only in different beds, but also in different parts of the same bed; and there is no plane of separation between them. This classification is based on the presence and character of the amygdules in the middle and upper division, and their infrequent occurrence in the lower.

The amygdules in the middle portion, and the more isolated ones in the lower, as a general thing, occupy the place of former constituents; while those of the amygdaloids proper have, to a great extent, been formed in pre-existing cavities of more or less regular form.

The changes that have taken place in the middle and lower portions of any bed are such as tend to produce a pseudo-amygdaloid. The first and ever-present stage of alteration is caused by the change of the residuary magma-base which fills the interstices between the crystalline constituents, and in places penetrates into, or is enclosed in, the interior of these. The physical and chemical character of this seems to have predisposed it to an easy change. It is now, as a rule, when seen in thin sections, a darker or lighter olive-green substance, and very soft under the needle (hardness not over 2.5). In polarized light it exhibits a fibrous aggregate polarization, and shows well its structure, which is short fibrous, converging towards the centre. The central portion shows sometimes little or no double refraction, but more generally it is filled with very minute polarizing spheres formed of radiating fibres. With one nicol, this substance shows only absorption for intensity. The contours are generally sharply defined by the feldspar and pyroxene crystals, and the result is usually a more or less wedge-shaped form.

The next step has been the change of the chrysolite. In the so-called greenstone, this has been only partial; but generally in the chrysolite-bearing beds it is complete. The result in thin sections is a faintly green substance, soft under the needle, and surrounded, within the original contours of the crystal, by a more or less opaque deposit of iron oxide, which also traversed it in fissures. The green substance shows by a well-defined cleavage in one direction that it is in thin laminæ. Between crossed nicols, these laminæ have an appearance of twin structure, polarizing the light in alternate lines of brilliant red and green. The whole pseudomorph becomes dark when the cleavage is parallel to a nicol plane; and some individuals, probably cut parallel to the cleavage, remain dark through a revolution of the stage. The substance is, therefore, very probably uniaxial. It has very appreciable absorption for intensity, and very feeble for color.

The augite was the next to undergo change. Generally in any thin section of the lower portion of a bed, a considerable proportion of the pyroxene is fresh, either throughout whole individuals or in parts of these.

In thin sections, by ordinary transmitted light, the pseudomorphous product is translucent, faintly light green, with a tinge of brown. Between crossed nicols, in its most characteristic form, it shows irregular lamellar aggregate polarization. It is very soft under the needle, and is traversed by red stained cracks corresponding to the irregular fissures in the parent pyroxene, and it is by these, together with the structure as seen in polarized light, that it is generally best distinguished from the product after residuary magma-base.

The mineral forming these pseudomorphs is very probably the result of a process which has removed lime and some iron, magnesia, and silica from the pyroxene and brought in water, and it is, probably, poor in alumina.

The plagioclase is generally the last constituent that has been altered to any great extent. The most usual product is chloritic. It is very usual to observe very minute particles of a green, apparently structureless substance, suspended in the interior of the feldspar in such a manner as to render the supposition quite possible that they are due to an alteration of enclosed particles of hyaline base. But an actual pseudomorphism of a chlorite after plagioclase is observable on a large scale. In the first stages, small tuft-shaped particles, consisting of laminæ or fibres radiating from a point, occur scattered through the interior of the feldspar, and these may wholly occupy a considerable portion of a crystal, while the rest still shows twin striation in polarized light. In the finished state no trace of the feldspar is visible except the outlines. The pseudomorph then shows an aggregate polarization due to a confusedly felted mass of minute chlorite tufts. The substance is poorly characterized.

The green substances which I have described so unsatisfactorily, as being undoubtedly pseudomorphous after residuary-base, pyroxene, and plagioclase, have in themselves no physical properties, recognizable under the microscope, which are sufficiently *persistent* to invariably characterize them respectively. Often the best means of distinguishing between them is in the internal structure of the aggregate, since this is intimately connected with certain physical characteristics of the original mineral which predetermined the mode of growth and gradual arrangement of the secondary product. In other instances, the presence or absence of cracks stained with iron oxide are characteristic.

Thus the change of the residuary base has resulted in a tendency to form bands parallel to the contour of the area, in a manner that indicates a gradual progress along concentric shells from the circumference inward or the reverse; while in the feldspar the growth appears to have begun without any regularity throughout the cleavage and twinning planes of the crystals. The pseudomorphs, after pyroxene, are almost invariably defined by the red-stained cracks, and slight mixture of brown in the green.

There is another occurrence of chlorite in which the progress of growth is from within outward. Throughout the pseudo-amygdaloid occur grains of chloritic substance, which in places reach a diameter of $\frac{1}{4}$ to $\frac{3}{8}$ inch, with often more or less irregular outlines, often nearly round or oval. These consist of a dark green mineral with $H = 2.5$, which fuses B. B. at 3 — 3.5 to a black magnetic slag.* In different beds, its texture under a hand-glass varies from amorphous to finely scaly. In thin sections, in polarized light, the substance often resembles closely that in the pseudomorphs after plagioclase, except in that it shows evident growth from within outward. There is no defined wall, as of a preexisting cavity, but the chlorite often sends out long arms, which surround or penetrate the adjoining primary constituents. In this manner the chlorite-like pseudomorphs after plagioclase and pyroxene, etc., are sometimes incorporated into these pseudo-amygdules. Very often one of these bodies has a large central area filled with closely packed radiating spheres, surrounded by fragments of a once continuous band with cross-fibrous structure, which evidently once formed the outer limit;

---

* For chemical analyses of this chlorite, see beyond under "Bed No. 87."

outside of these fragments is an outer chlorite area, resembling that in the centre, and generally bordered on its outer limit by a narrow cross-fibrous band which adapts itself closely to the primary constituents. The greater number of these bodies seem to have resulted from a gradual change of the primary minerals into chlorite by progress from molecule to molecule. At the first glance, the structure does not seem to confirm this view; for the narrow outer band enclosing a large central filling seems to suggest either, 1st, a pre-existing cavity, on the walls of which the thin outer layer was deposited as the older member and, within this, the central filling as the younger; or, 2d, the replacement by chlorite of a former secondary mineral, which was attacked at the same time, around its circumference, producing the outer band (shell), and throughout the interior.

Amygdules resulting from both of these processes are abundant in the amygdaloids proper; but they betray their origin in a marked manner, and differ essentially from these pseudo-amygdules.

Whatever the chemical nature of the process resulting in these pseudomorphs, the central area is the oldest member, while the outer band is the younger; and its cross-fibrous structure is only a transitional form destined to be changed to spheres with radiating structure. If we examine the structure of the outer band, we find that its line of contact with the primary minerals, or its axial line, is usually more or less serpentine, and that the cross-fibres, instead of being parallel to each other, are more nearly perpendicular to the axial line of the band, and form closely packed groups, in each of which the fibres radiate from a central point on the axial line, forming minute hemispheres, which bristle towards the interior of the body. The next stage of growth finished the other half of each sphere, and what was a cross-fibred band becomes now undistinguishable from the rest of the central filling, a new band having formed outside of the previous one. In places we find perfectly straight bands, with actually parallel cross fibres, which can hardly be supposed to break up into spheres; and indeed we find that new parallel bands are formed outside of these until the line of attack becomes crooked, when the normal mode of growth is re-established. The remnants of these straight bands are then preserved in the interior of the body.

Bed No. 96. — There are two other instances of pseudomorphs after plagioclase, which occur in the lower zone; viz., prehnite and quartz.

Bed No. 96, lying north of the "greenstone," in the Eagle River Section, is a rather coarse-grained diabase. It is dirty green, filled with small dull-gray feldspar crystals, and presenting on the fresh fracture numerous irregular-shaped, small, chalky-white spots. Examining the broken surface, under a 1½ inch objective, twin striation is well marked on some of the feldspar crystals, while others are too much altered to cleave, and are easily scratched by the needle. Grains of fresh pyroxene are abundant, and the chalky-white spots are found to be hard, and to resemble in structure, on a minute scale, the common prehnite amygdules of the rocks. There is also an abundance of a velvety, dark-green, very soft substance, with conchoidal fracture and resinous lustre, which is often seamed with a brilliant, black, metallic substance, apparently magnetite. This dark-green substance fills spaces between the other constituents, and often surrounds the prehnite-like bodies.

This prehnite-like mineral fuses readily in the flame of an alcohol lamp; it dissolves in heated muriatic acid, leaving pulverulent silica, and, in the filtrate, ammonia produces an abundant precipitate, slightly tinged with brown. There can be little doubt that the mineral is prehnite.

In thin sections, between crossed nicols, the prehnite bodies give the characteristic colors of this mineral, and have often a radiating structure generally starting from one point on the side. Often they consist of aggregated small masses, with the same structure, and too hard to be scratched by the needle.

A considerable portion of the feldspar crystals contain a greater or less quantity of these prehnite tufts, and not rarely the only vestige of the feldspar left is the contour of its crystal. Optical measurements, by Des Cloiseaux's method, on sections cut parallel to O, and on random sections in the zone $O : i.\bar{i}.$, together show that the feldspar is labradorite. Many of the crystals measured were partly changed to prehnite.

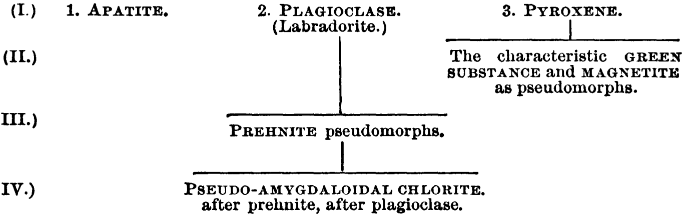
The prehnite is often changed to a more or less soft, white, semi-opaque substance, and is then almost invariably enveloped by a clear, green soft mineral, with radiating structure, which resembles the chloritic substance of the pseudo-amygdules already described. The plagioclase crystals also contain this green substance, and are, in places, represented by it alone.

This green mineral gives a greenish-brown streak, and fuses quietly before the blow-pipe to a black magnetic slag; it dissolves in muriatic acid, leaving a deposit of silica, and, in the filtrate, ammonia precipitates alumina and iron. There can be little doubt that the prehnitization preceded and mediated the formation of the pseudomorphs of this green mineral after feldspar.

The pyroxene has been more or less changed to its characteristic product; and in some instances this contains numerous seams of magnetite, as shown by a magnetized needle in scratching an uncovered section.

The feldspar crystals are in places traversed by long, slender needles of apatite. The pyroxene adapts itself sharply to the contours of the feldspar.

The paragenetic scheme would seem to be —


(I.)
1. APATITE.
2. PLAGIOCLASE. (Labradorite.)
3. PYROXENE.
(II.)
The characteristic GREEN SUBSTANCE and MAGNETITE as pseudomorphs.
(III.)
PREHNITE pseudomorphs.
(IV.)
PSEUDO-AMYGDALOIDAL CHLORITE. after prehnite, after plagioclase.

Bed 800 *feet E. of Hungarian lode.* — The occurrence of the pseudomorphism of prehnite after plagioclase is very beautifully illustrated in an extensively developed series of beds lying east of the Hungarian mine. These beds are remarkable as being almost free from pyroxene.

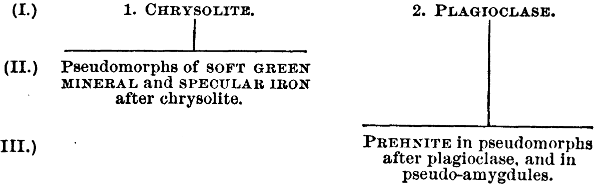
The rock from which I cut my sections is brownish-gray, fine-grained, with even, subconchoidal fracture. Specific gravity = 2.83. The naked eye detects greenish-white, irregular bodies of prehnite, from $\frac{1}{4}$ inch diameter down, and under the loupe the rock is found to be thoroughly impregnated with them. It also contains abundant minute grains of a soft, brown mineral, intimately associated with a brilliant black mineral, with metallic lustre, which is not attracted by the magnet, and is probably specular iron.

In the thin sections, the feldspar is found to have formed fully nine-tenths of the primary constituents. Its sections seem to indicate square, thick crystals instead of thin, tabular forms. A part of that which is still transparent shows no twinning, and some sections were observed in which the principal sections were parallel to the rectangular outlines, and which were probably orthoclase. The few optical measurements made on random sections in the zone $O : i\bar{i}$. did not give any higher results than would be required for oligoclase. No pyroxene was observed; and, while it is possible that some of the soft grains seen with the naked eye are derived from it, the appearances seem to indicate that they are pseudomorphs after chrysolite. They generally consist of a clear, slightly-greenish substance, which is in places amorphous, and in others contains minute fibres which polarize the light very feebly. This soft amorphous substance is surrounded and often traversed by the associated oxide of iron.

The plagioclase crystals, even where the twin striation in polarized light is still preserved, contain a greater or less number of small prehnite enclosures; where these are more abundant, the twin striation disappears, and in other parts of the field we find feldspar forms, presenting now a brilliant aggregate polarization, with the characteristic prehnite colors. More commonly the feldspar contours are lost, and we find pseudo-amygdules of prehnite of all sizes, and with the most irregular outlines. These often stand in such intimate connection with prehnite aggregates adjoining feldspar crystals, that it is impossible not to be convinced that the pseudo-amygdules are formed by a growth from a central point outward, attacking the feldspar crystals bodily from the outside. The pseudomorphs proper, on the other hand, result from a change which had countless starting-points in the interior of the crystal. Indeed, we have here a perfect counterpart to the formation of chloritic pseudo-amygdules, and chlorite pseudomorphs after plagioclase, which I have described above, except that here we have a process of prehnitization, while there it is one of chloritization.

A remarkable feature in these sections is the almost total absence of chloritic substance; and it is almost impossible not to see a connection in this with the absence of pyroxene. Indeed, it shows that it is at least quite possible that the extensive change to chlorite in these rocks may be preceded, or mediated, step by step, by the formation of prehnite, which, in its turn, is changed to chlorite, under the co-operation of the decomposition products of pyroxene.

The paragenetic scheme for this rock may be written thus: —


(I.)
1. CHRYSOLITE.
2. PLAGIOCLASE.
(II.)
Pseudomorphs of SOFT GREEN MINERAL and SPECULAR IRON after chrysolite.
(III.)
PREHNITE in pseudomorphs after plagioclase, and in pseudo-amygdules.

Bed No. 94. — Specific gravity = 2.94. Coarsely crystalline. The most prominent constituent, forming 40–50 per cent of the rock, is feldspar, in narrow, tabular crystals, which are often one inch long. As a rule, the feldspar crystals show, on the cleavage planes, broad bands free from twinning, except where two or three almost microscopic plates of plagioclase are interposed, and a considerable number of the larger crystals are almost wholly free from striation. They are flesh-red from having begun to change. The spaces between these crystals have dark-green and black colors, and, under the microscope with a low power, are found to consist, in part, of a grayish-green, compact mineral, with semi-conchoidal fracture, very soft under the needle-point, and containing veins and fragments of a brilliant black mineral, which, from its streak, and action under the magnet, appears to be magnetite. Other spaces consist of a lighter green mineral, with radiating fibrous structure in segments of spheres, and very soft under the needle. With this light-green mineral are associated aggregated crystalline grains of quartz.

Examining different parts of the specimen, all the constituents are found to envelop long, slender, hexagonal prisms of limpid white apatite.

In uncovered thin sections, under the microscope, we find that the red color of the feldspar is due to a staining on the sides and along the planes of twinning and in fissures. Where the crystals have not become sufficiently altered to be unrecognizable as such, they are not scratched by the needle.

Within the spaces between the feldspar crystals are isolated remnants of augite, in places still transparent, fresh and smoky-brown, but generally surrounded and veined with a slightly translucent grayish-green substance, which is very soft under the needle, and contains veins and grains of magnetite: it is the compact, soft, green mineral mentioned above. The magnetite is here porous in structure, and, when scratched with a magnetized needle, gives a shining black streak, and leaves particles adhering to the needle: facts which indicate that it forms a network of filmy veins intersecting the soft, green substance in all directions, like the cement of a breccia.

The light-green mineral with radiating structure is here seen to be entirely distinct from the grayish-green substance; it is very soft under the needle, and contains no magnetite, but is associated with quartz.

In polarized light some of the feldspar crystals are found to be beautifully marked throughout with thin twin striæ; but these are generally either absent, or only two or three narrow ones are associated with very broad unstriated bands.

Two systems of twinning occur among the feldspar crystals, cutting each other nearly at a right angle. In the greater number of instances, the composition plane is the plane of symmetry; in these double twins, a long, sharply defined crystal will have broad areas free from longitudinal striæ, and apparently of orthoclase, with a few longitudinal narrow bands of a triclinic feldspar intertwinned with it on one side (composition plane = plane of symmetry), while the broad band of supposed orthoclase is crossed here and there by twinned thin laminæ of triclinic feldspar, probably having *O* for the composition plane. These two sets of triclinic individuals generally meet with a more or less acute angle, but in one instance I obtained a very certain measurement of 89° 30′ — an observation that seems to leave little doubt that we have here a combination of orthoclase with triclinic feldspar, similar, as regards crystallographic structure, to the orthoclase-albite crystals of Harzburg, described by Streng.*

The thin sections of the rock we are describing leave no doubt that orthoclase is an essential primary constituent.

I was able to measure some microscopic crystals directly under the microscope, the angle $O : i\bar{\imath}$ getting 90° 10′ as the result on an unstriated individual, and 93° 29′ on the striated ones.

Measurements of the entering angle on the cleavage plane, with a reflecting goniometer, gave 93° 24′.

Optical measurements by Des Cloiseaux's method on sections parallel *O*, and on random sections in the zone $O : i\bar{\imath}$, determine the feldspar to be oligoclase.

The most prominent appearance of change is the red staining, which is due to the presence of countless minute particles of translucent red or brown iron oxide, which is generally most abundant near the edges, or along the cleavage planes, and in cracks. It is generally more or less present throughout the crystals, though some of these are nearly free from it, except along the above-defined lines.

Where freshest, the feldspar is still clouded, and, under high powers, this is seen to be due to the presence of innumerable minute particles of irregular shape, of a bluish-gray color, and clear, except a narrow dark rim, which seem to be inclosed particles of residuary base.

Besides these, there are large numbers of particles of green substance in warped thick flakes or grains, which seem to aggregate to form wisps or sheaves of long radiating needles. When examined with only the polarizer, these last show an appreciable absorption.

In many crystals, the mass is either clouded through and through with the iron oxide, or is occupied to the extent of from twenty to fifty per cent of its area by the sheaves of radiating green mineral, or both substances are present. The green mineral also forms veins, filling cracks in the feldspar, and is clearly the light-green, soft substance already mentioned. The larger sheaves, occupying the whole thickness of the thin section and the veins, permit some optical determinations on the mineral. Examining it with the polarizer, it shows a marked dichroism, being deep bluish-green, when the longer axis of a needle coincides with the shorter diagonal of the nicol, and light, faintly brown or greenish-brown when at 90°. Between crossed nicols some of the needles become dark when the longer axis is parallel to a nicol-plane; but there often appears to be an angular difference of several degrees. It seems, therefore, considering its softness under the needle, and its optical qualities, to be possibly a monoclinic chlorite. Where the change has gone very far, only fragments of the feldspar remain, surrounded and penetrated by the chlorite and granular quartz.

---

* Streng. Feldspath Studien. Leonhard u. Geinitz, Neues Jahrbuch für Mineralogie, 1871, p. 719.

One or two crystals were seen having the contours of feldspar individuals sharply defined, but consisting of granular quartz, showing aggregate polarization, and containing apatite needles and the chlorite. They appear to be pseudomorphs of quartz after feldspar. With the chlorite occurs a yellowish-green chloritic mineral, consisting of closely packed minute spheres, made up of spicules or foliæ, radiating from a centre; they are double-refracting, but show no absorption.

As a rule the augite crystals have disappeared, as such; but, in places, individuals are observed which are in one part perfectly fresh, and in others show the stages of change. Where freshest, they are transparent, almost colorless, with a smoky tinge, and have many irregular fractures, and, in places, parallel cracks, indicating cleavage.

Where they are apparently perfectly fresh, the principal foreign particles they contain are minute ones of a bluish-gray color or, in the larger grains, deep sapphire-blue, and have a narrow, dark rim. These are often in sharply defined rhombic prisms, but more generally of irregular shape, and sometimes connected by hair-like necks. They are almost always arranged in warped planes, in some of which they are much scattered, in others closely packed. A linear arrangement was also observed.

Besides these, the pyroxene contains slender straight rods, which are opaque and black, possibly because of their slender proportions. They are in groups of parallel rods, two groups in places, intersecting each other, and each group being parallel to a different axis. These groups of rods become in places the skeleton of a curious structure; the rods in parallel rows being connected by a bottle-green substance, so as to form parallel uneven planes, like brush-fences, in which the rods represent the posts, and the bottle-green substance the brush, interwoven horizontally, and so closely as to obscure the brush-structure. I can think of no better illustration. In places, this structure, exists without any visible black rods.

Where the augite is clouded by a beginning change in the interior, we find these planes of bluish particles and the brush-fence structures to be starting-points, having, in those representing the first stages, only slightly diffused yellowish-green substance; in others, the primary interpositions become more and more obscured, and the planes and arrangement of bottle-green substance are wholly lost in the green mass which penetrates with a serrated front into the fresh augite. This green substance also attacks the crystal from the outside, and along the cracks. Under a high objective the contact resolves itself into a jagged line.

A considerably altered augite crystal is surrounded by a green mass, and more or less broken up by cross-bars of the same substance, while the interior of the remaining augite fragments is often occupied by masses of the green substance which had the interpositions for starting-points.

This alteration product is yellowish-green where very thin, and translucent dirty-green or grayish-green where thicker. It is composed of countless minute stars, indicating radiating structure, and is double-refracting, but shows no absorption for color, and little or none for intensity. The same substance occurs, to a slight extent, in the ruined feldspar with the chlorite, which it sometimes borders.

The green product is associated with magnetite in large and small particles, and, where the change progressed along a crack, the green band has a median line of more or less closely contiguous films and grains of magnetite, which corresponds with the structure, as observed in reflected light on the uncovered sections.

In the rock from the Eagle River, district 94, the augite contains only isolated particles of red ferrite, and then, generally, only in the planes of bluish interpositions, and where these are near the altered portions. But in an almost identical rock, coming from the same zone, north of the Delaware mine, and in which the augite seems to have been wholly changed, an examination in reflected light shows the magnetite surrounded by an opaque mass of red oxide, which, further from the magnetite, resolves itself into a cloud of minute particles of transparent brown, or red ferrite suspended in the green alteration product. Optical measurements on sections of feldspar in the zone $O: i\bar{i}$ in the preparations of this rock gave the same result as in bed 94.

The abundant apatite needles are characterized by their hexagonal sections, or, where cut longitudinally, by their very feeble double-refraction. They often contain many long and straight hair-like black rods, or prisms, ranged strictly parallel to the longer axis of the crystal. Besides these, they contain abundant fluid cavities with dancing bubbles, which did not diminish in size when heated to 95° C.*

They enclose also globular or egg-shaped drops of a greenish-brown substance; on examining these in crystals cut perpendicularly to the longer axis, they were found to be isotrope. There can be no doubt, I think, that these are portions of the original fluid magma, out of which the rock crystallized. We owe to the almost indestructible character of the apatite, and to its lack of double-refraction in one direction, the preservation of this glass, and our ability to recognize its amorphous nature, and thus to obtain the strongest circumstantial evidence of the eruptive origin of these rocks.

The relative ages of the constituents may be represented by the following scheme: —

(I.)	1. APATITE.	2. OLIGOCLASE and ORTHOCLASE.	3. AUGITE and MAGNETITE?
(II.)		*c*. FERRITE. *d*. CHLORITE monoclinic? *e*. QUARTZ.	*a*. Yellowish-green mineral. *b*. MAGNETITE?

Bed No. 61. — Among the changes that have resulted in the formation of pseudo-amygdaloids is one which seems to be rare, for I have met with it in only one of the several hundred sections I have cut of these rocks. It is the formation of pseudo-amygdules of analcite on a large scale. The rock is from the *lower part* of bed No. 61 of the Eagle River Section. It is greenish-gray, and breaks with an uneven and somewhat schistose fracture. It is filled with irregularly shaped grains of a white mineral, which fuses, at about three, to a clear glass containing air bubbles; it dissolves in muriatic acid, leaving a deposit of silica, and the filtrate gives with ammonia an abundant precipitate of alumina; in thin sections it is transparent and colorless, and shows its isotrope character by remaining dark during a revolution between crossed nicols. The mineral is undoubtedly analcite. Isolated bands occur, showing very feeble double-refraction.

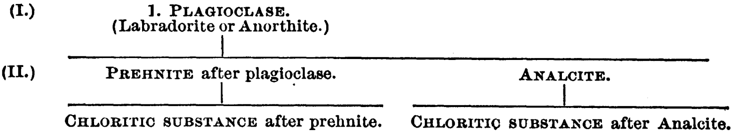
In thin sections, besides the analcite, the most conspicuous constituent is the green, soft, chloritic substance characteristic of the pseudo-amygdules. In this lie isolated plagioclase crystals, some showing twin striation in polarized light, and others in which this has been lost. Optical measurements on these crystals, on sections cut in the zone *O: iī*, indicate that the feldspar is either labradorite or anorthite. A large part of these crystals show an aggregate polarization so closely resembling that of the prehnite pseudomorphs after plagioclase, that there is little doubt that they are partly changed to prehnite. The change to chlorite is evident, in all stages, from chlorite disseminated through the plagioclase, to finished pseudomorphs and pseudo-amygdules.

---

* This is not corrected for the influence of Beck's $\frac{1}{10}$ immersion objective.

The analcite bodies are seen to have no true amygdule-walls, but to penetrate the matrix in the most irregular manner, as in pseudo-amygdules, which they really seem to be. They are traversed by seams of chloritic substance, and are often changed into this to a considerable depth on the sides, besides containing in places groups of the same chloritic substance in the interior. They are also cut by seams of calcite, which also traverse the matrix. The chloritic substance seems in places to have formed finished pseudomorphs after the analcite. The chloritic substance, resulting from change of analcite, is less clear, and much finer textured than that resulting from the change of feldspar.

There are no visible traces of pyroxene. It seems to be quite probable that the analcite is derived from the plagioclase, but I have no data for determining its relative age as compared with that of the prehnite. As a rule, the secondary alkaline silicates form only in the amygdaloids proper, and in veins.


(I.)
1. PLAGIOCLASE.
(Labradorite or Anorthite.)
(II.)
PREHNITE after plagioclase.
ANALCITE.
CHLORITIC SUBSTANCE after prehnite.
CHLORITIC SUBSTANCE after Analcite.

Bed No. 22, of the Eagle River Section, has forty feet of lower zone, and sixteen of pseudo-amygdaloid. Thin sections of the diabase from the lower zone show the plagioclase crystals mostly very fresh. Optical measurements on sections in the zone *O: iī*, indicate that the feldspar is labradorite. They are closely surrounded by the younger pyroxene, which is in part very fresh, but in places is changed to its characteristic pseudomorphs. This secondary mineral is better marked here than is usual; it has well-defined, perfect cleavage, strong absorption for intensity, being dark when the cleavage lines coincide with the shorter diagonal of the nicol. Between crossed nicols, darkness occurs when the cleavage lines are parallel to a nicol plane. I observed no instances in which it revolved dark. These characteristics indicate an orthorhombic crystallization. In ordinary transmitted light in thin section, the mineral is olive-green, traversed by iron-stained cracks.

In the pseudo-amygdaloid, while portions of many of the plagioclase crystals are clear and fresh, they are all more or less changed to prehnite, and exhibit every stage from the beginning to the perfect pseudomorph. Prehnite also forms countless pseudo-amygdules, from microscopic size up to one-half inch diameter, which have clearly formed at the cost of the plagioclase. Chlorite occurs in the same manner as the prehnite, forming pseudomorphs after plagioclase, and pseudo-amygdules.

A pseudo-amygdaloid, south of Houghton, contains abundant pseudo-amygdules of prehnite, often an inch or more in diameter. Some of these were found to be partially changed to a coarsely foliaceous chlorite. The prehnite has long-radiating tabular structure. The change has begun between the plates, and in places has wholly altered parts of the prehnite; the pseudomorphs preserve the same radiating structure as the prehnite. In a moderately thin section, the chlorite is dark green and dichroitic, changing from dark green, when its cleavage lines are parallel to the shorter diagonal of the nicol, to a smoky brown when parallel to the longer diagonal.

Small scales pressed between slides in balsam revolved dark between crossed nicols; it is therefore uniaxial.

The feldspar of this rock is apparently either albite or oligoclase, — in all probability the latter; for the highest angle found in ten optical measurements on random sections in the zone $O \mid i\bar{i}$ was 29°.

AMYGDALOIDS.

The uppermost zone — the amygdaloid — in many beds is, in several respects, essentially different from the rest of the rock. In these instances, the matrix has a much finer texture, often quite aphanitic, even where the lower and pseudo-amygdaloid zones of the same bed are quite coarse grained and distinctly crystalline. The amygdules have generally spherical or ovoidal forms, filling cavities with sharply defined walls. In some rare instances, the amygdules are long and cylindrical, and arranged perpendicular to the plane of bedding.

In thin sections, the difference between the texture of the matrix and the texture of the lower zone of the same bed is very apparent. While the primary constituents, when preserved, do not differ apparently in quality, they are of much smaller size, and sometimes show an arrested development and microfluidal structure. Here, too, the amygdules have sharply defined, evenly curved contours, differing wholly in this respect from the pseudo-amygdules of the lower zones of the same bed. Often also the primary minerals of the matrix are much more minute in the immediate neighborhood of the amygdules than away from them, and their disposition seems also to have been influenced by the presence of the amygdaloidal cavity. The color of the amygdaloid matrix varies between different shades of dark greenish brown, chocolate-brown, dull light green, and brilliant light green. All these colors often occur in the same bed, or even in the same specimen, and, like the differences in hardness, — from 3 to 7, — are due to metasomatic changes.

There is one variety — the *scoriaceous amygdaloid* — which occurs less often than the others, but is always strongly characterized. It consists of true amygdaloid and sandstone curiously associated. The amygdaloid is in contorted forms, from an inch or less to several feet in size, with a sharply defined, often wrinkled, surface, and wholly enveloped with sandstone. The glaciated surface of the outcrops of this rock often present at the first glance the appearance of a conglomerate, in which here the amygdaloid, there the sandstone, appears to form the cement. Thin sections show that we have to do with a true sandstone of quartz and feldspar derived from quartz porphyry, and identical with that which forms the great sandstone beds of the copper series; and that the other constituent is a true amygdaloid.

The conditions, as studied on the ground, indicate that *these* beds are volcanic scoriæ, buried in the littoral sand. To this variety belong the famous "Ash-bed" of the Copper-falls and Phœnix mines, and the beds worked in the Hancock and South Pewabic mines.

Bed No. 87 of the Eagle River Section has an actual thickness of 154 feet, of which 7 feet belong to the amygdaloid, 23 to the pseudo-amygdaloid, and 124 to the lower zone. The lower zone has a rather fine grain, and shows to the naked eye only green crystals of feldspar, and irregular-shaped small spots of dark green chlorite. These constituents give to the rock a dirty gray green color, spotted with dark green. The powder yields some magnetite.

In thin sections, from the lower zone, we can distinguish plagioclase, augite, an impellucid, dirty gray, unindividualized substance, containing often radiating colorless needles of a feebly double-refracting substance, perhaps apatite; besides these, there are the abundant secondary products.

The augite, which is the least altered constituent, is generally highly fissured, and in places altered to its characteristic chloritic product, more or less associated with red and black iron stains, which are possibly the source of some of the magnetite.

The plagioclase retains in many places its twin-striation in polarized light, but, even where freshest, it contains many tufts of radiating fibres or laminæ of chlorite, and the sections show that a large part of the feldspar has been changed to pseudomorphs and pseudo-amygdules of chlorite. Optical measurements on random sections in the zone *O: iĭ* give only low angles that may belong to either albite or oligoclase, here undoubtedly the latter. The specific gravity of the rock is 2.73, which also points to oligoclase.

The external appearance of the middle zone differs from that of the lower in having a rather coarse grain, and in that the feldspar crystals are pink and of all sizes, from $\frac{1}{5}$ inch down, while the very irregularly shaped masses of dark green chlorite often reach $\frac{1}{3}$ inch in diameter.

In thin sections from the middle zone, I found the pyroxene wholly represented by its characteristic pseudomorphs with iron-stained cracks; the plagioclase is also much more altered.

The formation of the chlorite pseudo-amygdules after the manner already described is beautifully illustrated in this rock.

This chloritic substance appears, under a glass, both as a compact and as a very finely scaley, dark-green mineral. The hardness of the compact portions is 2.5. It fuses at 3–3.5 to a dull black magnetic globule. It dissolves in muriatic acid, leaving pulverulent silica, and the solution contains alumina, protoxide of iron, and magnesia; an appreciable amount of both potash and soda was found, both after boiling in water and in the acid solution. (See complete analysis of this mineral.)

In the thin sections, the radiating laminæ are decidedly dichroitic, being straw-yellow when the longer direction coincides with the longer diagonal of the nicol, and bluish green when parallel to the shorter diagonal. Between crossed nicols it seems to be uniaxial, for the crystals become dark when the longer direction coincides with a nicol plane, and portions were found which revolved dark. Its appearance in polarized light corresponds very closely with that of a section of diabantite* which Mr. Hawes kindly sent me; but it differs in its hardness, diabantite being only 1.

The following analyses (made for me by Mr. Woodward, in the Laboratory of the Sheffield Scientific School) are of specimens from the lower and middle parts of bed No. 87, and of the chloritic mineral forming the pseudo-amygdules.

---

* On Diabantite. Geo. W. Hawes, Amer. Jour. Sci., June, 1875, p. 454.

BOTTOM OF BED 87.		MIDDLE OF BED 87.	
SiO_2	46.32	SiO_2	49.20
Al_2O_3	15.95	Al_2O_3	16.00
Fe_2O_3	2.86	Fe_2O_3	3.03
FeO	8.92	FeO	7.10
MnO	.89	MnO	1.17
CaO	10.28	CaO	3.44
MgO	4.08	MgO	6.98
TiO_2	2.78	TiO_2	2.26
K_2O	1.23	K_2O	1.31
Na_2O	3.56	Na_2O	5.05
H_2O	3.25	H_2O	4.51
	100.12		100.05

Both rocks are too highly altered to permit a calculation of the mineral constituents.

Chloritic pseudo-amygdules in bed No. 87.				Analysis of chloritic amygdules from the rock under the Quincy copper-bearing bed. By MacFarlane. (Geol. of Canada, 1866, p. 154.)	
		Per cent. ÷ at. Weight.			
SiO_2	29.56	.492	2.1	SiO_2	30.59
Al_2O_3	22.41	.207	1.	Al_2O_3	26.07
Fe_2O_3	4.38	.027			
FeO	22.20	.308	2.5	FeO	22.01
MnO	1.18	.016			
CaO	2.16	.038		CaO	1.92
MgO	8.36	.209		MgO	12.36
K_2O	.15	.001			
Na_2O	.49	.008			
H_2O	9.07	.503	2.1	H_2O	7.23
	99.89				100.18

The mineral of the pseudo-amygdules approaches more nearly to delessite than to any other of the chlorites. I have added an analysis of a similar pseudo-amygdaloidal chlorite from another part of the district.

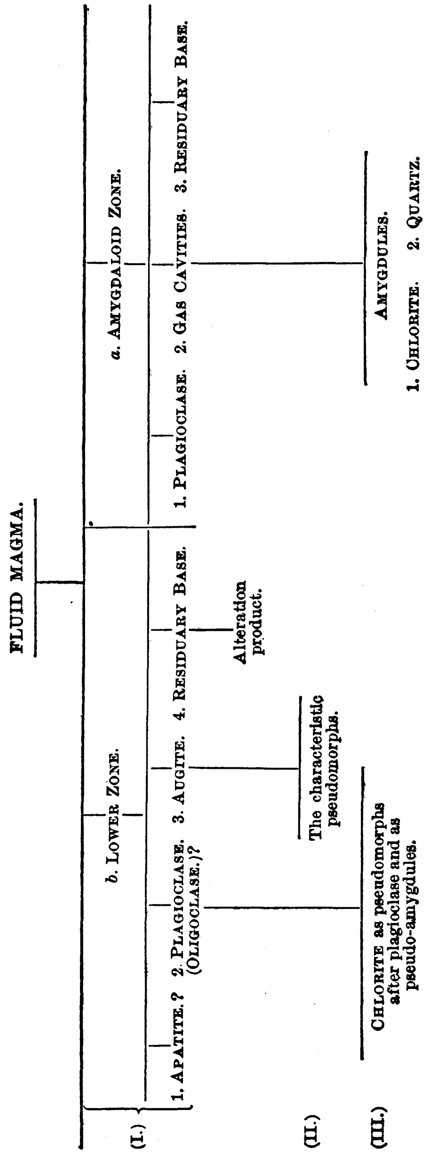
The amygdaloid of this bed is compact — almost aphanitic — in texture, and is reddish-brown to greenish brown in color. Nearly onefifth of the rock is occupied by amygdules averaging $\frac{1}{8}$ inch diameter, but sometimes much larger, and consisting chiefly of quartz covered by, and more or less impregnated with, chlorite. In the thin sections, the matrix consists chiefly of small plagioclase crystals, in which the twinning is still more or less apparent in polarized light, but they show marked alteration. The spaces between the plagioclase crystals are filled with an impellucid mass of brown particles of iron oxide, and confused, often radiating, long, slender, colorless, translucent crystals. These crystals are feebly polarizing, and at first sight appear like apatite, but I observed no hexagonal sections. They often start out from the end of a feldspar crystal and radiate from this, which, taken in connection with their appearance, renders it quite likely that they are feldspar microlites arrested during development into crystals. I noticed no pyroxene, and only very isolated apparent pseudomorphs after it. The impellucid substance between the feldspar microlites contains much soft, green, chloritic substance. As pyroxene in these rocks shows itself to have always crystallized after the feldspar, we should, perhaps, not expect to meet with it where the rock solidified before the feldspar microlites had united to form finished crystals.

The amygdules have almost always sharply defined, smooth walls, and are then bordered by a circumference of the unindividualized substance with its feldspar microlites, and these latter are then arranged in a manner with reference to the amygdule that seems to clearly indicate the exertion of a force by the cavity on a surrounding semifluid medium.

In places, the sharply defined outline and the unindividualized border are missing, and the formation of a pseudo-amygdule has taken place, often more or less enveloping the true amygdule.

The amygdules consist chiefly of quartz in crystalline aggregates, filling the interior, and surrounded by a mural lining of chlorite, consisting of long, thin narrow plates, which are either orthorhombic or uniaxial, and which bristle toward the interior. Long radiating tufts of these plates penetrate far into the interior of the pellucid quartz crystals, indicating that the chlorite lining is older than the quartz.

Paragenesis: —


FLUID MAGMA.
a. AMYGDALOID ZONE.
1. PLAGIOCLASE.
2. GAS CAVITIES.
3. RESIDUARY BASE.
AMYGDULES.
1. CHLORITE.
2. QUARTZ.
b. LOWER ZONE.
1. APATITE.?
2. PLAGIOCLASE. (OLIGOCLASE.)?
3. AUGITE.
4. RESIDUARY BASE.
Alteration product.
The characteristic pseudomorphs.
CHLORITE as pseudomorphs after plagioclase and as pseudo-amygdules.
(I.)
(II.)
(III.)

Bed No. 69 of the Eagle River Section consists of fifty-six feet of the lower zone, eleven feet of pseudo-amygdaloid, and six feet of amygdaloid.

The lower zone is a fine-grained, dirty-green rock with uneven fracture. It is easily scratched; has specific gravity 2.87–2.95, and the powder yields a little magnetite.

The thin sections resemble those of the lower zone of bed 87. The plagioclase is much altered, — containing in the freshest many tufts of chlorite — and is often represented only by pseudomorphs of chlorite, and in places these are merged into chlorite pseudo-amygdules.

The augite is in part very fresh, in part changed to its characteristic pseudomorph.

The amygdaloid is a very compact, hard rock, with subconchoidal fracture. It consists of very irregularly mixed brown and green portions, both hard, the brown abounding in amygdules, from one-third inch diameter down, chiefly of prehnite; often of prehnite as an outer member, and a central filling of quartz in some, in others calcite. The green contains fewer apparent amygdules.

Thin sections of the brown part show the sharp outlines of comparatively large porphyritic feldspar crystals, and of countless long slender feldspar microlites separated by an opaque brown substance. These feldspar forms are now occupied by brilliantly polarizing aggregates of prehnite.

Splinters of this brown matrix fuse in the flame of an alcohol lamp.

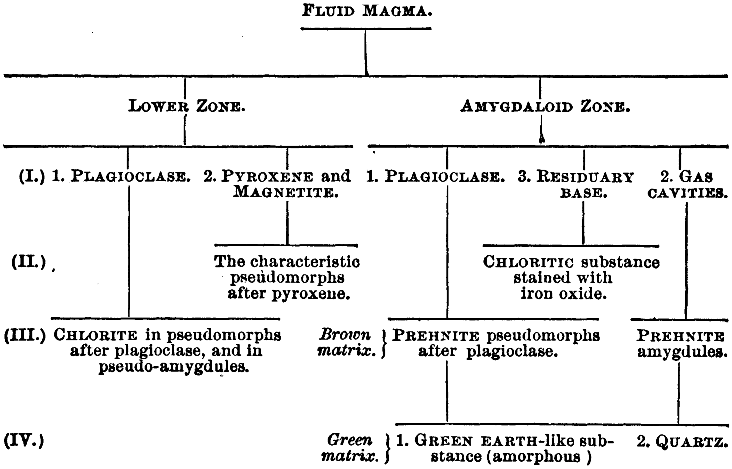
Some of the feldspar forms contain a large amount of a soft, light-green, seemingly amorphous mineral, which is, probably, pseudomorphous after prehnite; the rest of the pseudomorph in these cases *seems* to be quartz.

The amygdules have very sharply defined contours, and form brilliantly polarizing aggregates of prehnite. Quartz occurs in seams which cut through the prehnite of the matrix, and of the amygdules.

An examination of thin sections of the green parts shows that they are derived from the brown. They consist still to a great extent of prehnite, and many pseudomorphs of this after the feldspar are visible; but it is everywhere more or less changed to the light-green, soft substance (of which some was seen in the brown variety), and considerable areas of the field are wholly changed to this substance, which is thoroughly cut up by curving cracks of irregular shape and size, which are evidently due to contraction, and are now filled with quartz. But little of the brown staining seen in the brown variety is present here: the iron oxide causing it has, perhaps, gone towards forming the green-earth-like alteration product of the prehnite. Splinters of this variety show under the loupe by transmitted light, nearly opaque, light-green portions, separated by transparent white. The white fuses in the flame of an alcohol lamp.

The specific gravity of the brown part, taken where there were only very small amygdules, was 2.80; and that of the green, 2.83.

Paragenesis: —


FLUID MAGMA.
LOWER ZONE.
AMYGDALOID ZONE.
(I.) 1. PLAGIOCLASE.
2. PYROXENE and MAGNETITE.
1. PLAGIOCLASE.
3. RESIDUARY BASE.
2. GAS CAVITIES.
(II.)
The characteristic pseudomorphs after pyroxene.
CHLORITIC substance stained with iron oxide.
(III.) CHLORITE in pseudomorphs after plagioclase, and in pseudo-amygdules.
Brown matrix.
PREHNITE pseudomorphs after plagioclase.
PREHNITE amygdules.
(IV.)
Green matrix.
1. GREEN EARTH-like substance (amorphous)
2. QUARTZ.

HANCOCK MINE.

A specimen of chocolate-brown amygdaloid, from the halvans of the Hancock mine, contains beautiful amygdules of a dark green finely scaly chlorite, each one surrounded by a narrow ring of quartz. The matrix contains some grains that seem to be pyroxene, and some of the feldspar crystals, though much altered, still show twin-striation. But whole groups of the feldspar have been replaced by quartz in such a manner, that the quartz polarizes the light as an integral individual throughout the area of each group. The pyroxene grains and pseudomorphs within the areas of these groups have not been changed to quartz.

The chlorite of the amygdules is highly dichroitic, being green when the longer axis of the laminæ coincides with the shorter diagonal of the nicol, and yellow when perpendicular to this. Portions revolve dark between crossed nicols, as did also scales pressed in balsam between glass. It is therefore uniaxial. The quartz which forms the outer layer of the amygdules is connected with, and really forms part of, veins which traverse both the matrix and the chlorite of the amygdules. In doing this, it penetrates between some of the laminæ, and encloses others in a manner that proves it to be younger than the chlorite.

Bed No. 64.—The amygdaloid of bed 64 of the Eagle River Section has about sixty per cent of its volume occupied by amygdules, sometimes wholly prehnite, sometimes an outer layer of white prehnite, and a central filling of calcite. The matrix is chocolate-brown, and has a crystalline texture wholly foreign to the melaphyres, and more resembling that of a fine-grained, somewhat oxidized spathic iron ore. Its hardness is 6; fusibility 2–2.5; it dissolves in muriatic acid, leaving pulverulent silica, and the solution contains abundance of alumina and lime; in thin sections it is seen to be clearly orthorhombic, and polarizes the light with the same colors as prehnite, which it undoubtedly is. In thin sections, by ordinary light, the first things we see are the characteristic outlines of plagioclase crystals, filled with a limpid colorless substance, while all the interstitial spaces are filled with a less clear substance, colored brown by countless particles of iron oxide.

Examining it between crossed nicols, a remarkable change takes place. The plagioclase outlines are still sharply defined by the abundance of particles of iron-oxide suspended in the interstitial substance; but every thing except these brown particles is changed to prehnite. In places, the feldspars are each occupied by a fine-grained aggregate of prehnite; but often the latter mineral has crystallized more freely a group of long, radiating, tabular individuals, reaching with brilliant red and green colors across whole groups of plagioclase crystals and the interstitial spaces, and sometimes well into an amygdule without a break in the integral polarization of each plate.

Below the amygdaloid of bed 64, just described, there are several beds (with an aggregate thickness of twenty feet) forming apparently a transition into a pseudo-amygdaloid. The rock of these beds has a more or less light green color, a compact, aphanitic matrix, in which lie abundant amygdules $\frac{1}{8}$ inch and less in size. Many of these are filled with prehnite; as many more are cavities lined with rosy crystals of adularia, while others contain both of these minerals. The feldspar crystals in the cavities are sharply defined prisms, terminated at the free end with the basal plane. In thin sections, the matrix contains much pyroxene unaltered, except that it is much broken.

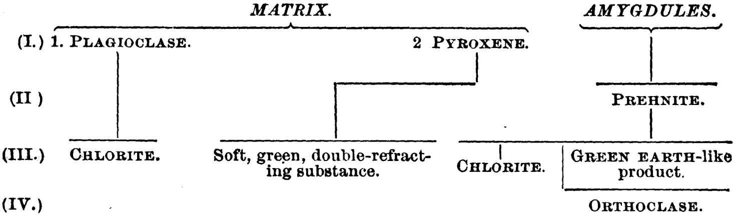
The plagioclase is all much altered, and a considerable proportion of the crystals is changed to chlorite. Where they are still colorless, they have lost the twin striation in polarized light.

The amygdules have generally, not always, sharp outlines. Some are of unaltered prehnite. Others, which have evidently consisted of prehnite with long radiating structure, are more or less altered to a soft, homogeneous, impellucid, green substance, which seems to be structureless, or to polarize the light only very feebly. It is a frequent alteration product of prehnite in these rocks. Some of the amygdules are wholly changed to chlorite. In most of the amygdules containing altered prehnite, the orthoclase occurs, showing aggregate polarization, and intimately associated with small fragments of prehnite, partially altered to the green substance; and while these are scattered through the orthoclase aggregate, they show in polarized light that they are merely remnants of a formerly continuous radiating mass of prehnite, the rest of which has been changed to orthoclase. As a rule this change has been accompanied by a large diminution of volume, resulting in a central empty cavity, into which the feldspar crystals project freely crystallized, and show there integral polarization.

The appearances seem to indicate that the pseudomorphs of orthoclase were formed after the partial destruction of the prehnite.

The pyroxene of the matrix has, in places, been altered to a bright yellowish-green, soft, double-refracting substance: none of the characteristic pseudomorphs were seen.

The paragenesis, in so far as it is determinable, is —



The melaphyre proper, which forms the lower member of bed No. 64, is a dark green, almost black, cryptocrystalline rock, which is easily scratched with the knife. Under the microscope, it is found to consist chiefly of plagioclase in very small crystals, a soft, green mineral, probably pseudomorphous after olivine, minute grains of augite, and occasional small, often wedge-shaped, occurrences of a green soft substance, occupying the interstices between feldspar crystals.

The feldspar appears, from optical measurements in the zone $O : i\bar{i}$, to be anorthite.

The augite is apparently fresh, and is very subordinate in quantity and size of individuals. Next, as regards quantity, to the feldspar, is the soft, green mineral. It is in rather rounded grains, suggesting rectangles with the corners rounded off, and elongated hexagons. The contours are not broken by the feldspar or augite crystals, from which they would seem to be the oldest constituent. They are strongly marked by thick, parallel, transparent, colorless lines, indicating open cleavage-cracks, show strong absorption for intensity, and become dark between crossed nicols when these lines are parallel to one of the nicol undulation-planes. Many were seen which showed no parallel lines, and these were, probably, cut parallel to the plane of cleavage, but none of them revolved dark between crossed nicols; the mineral is, therefore, probably orthorhombic. There can be little doubt that this mineral is pseudomorphous after olivine. Its contours are identical with those of the olivine in 108. The parallel structure is there represented by the tendency to a fibrous structure; and both the alteration product and the fresh olivine of the same individual are dark, when the direction of these fibres is parallel to one of the nicol undulation-planes.

There are also present many small pseudo-amygdules, filling the wedge-shaped interstices between the feldspars.

The annexed analyses of specimens from the three members of bed No. 64 serve to throw some light on the primary mineral constitution of the rock, and on its alteration. The calculation of the primary minerals in the fresher, bottom rock, can be only roughly proximative, while the optical measurements indicate a predominance of anorthite. The analysis confirms this, and points to the presence of a little soda, or soda-lime feldspar.

In the analysis from the middle, or amygdaloidal region, we find a loss of one-third of the soda; and a gain in lime, which marks the alteration of the feldspar to prehnite. The potash belongs to the orthoclase, which is pseudomorphous after prehnite.

The analyses were made for me by Mr. Woodward, of the Sheffield Scientific School.

Melaphyre. Lower Zone of Bed 64.	Per cent, ÷ At. Weight.	Orthoclase.	Albite.	Anorthite.	Pyroxene.	Magnetite.	Residue representing the product after olivine and the pseudo-amygdules.	Middle Zone (pseudo-amygdaloid), Bed 64.	Per cent, ÷ At. Weight.	Prehnitized Amygdaloid of Bed 64.	Per cent, ÷ At. Weight.
SiO_2 . . 47.74	.795	.006	.186	.260	.170		.173	SiO_2 . . 42.83	.714	SiO_2 . . 42.71	.711
Al_2O_3 . . 16.75	.162	.001	.031	.130				Al_2O_3 . . 16.58	.161	Al_2O_3 . . 14.93	.145
Fe_2O_3 . . 2.55	.015					.015		Fe_2O_3 . . 4.42	.028	Fe_2O_3 . . 7.45	.046
FeO . . 6.31	.087				.024	.014	.049	FeO . . 3.81	.052	FeO . . 3.48	.048
TiO_2 . . 1.02	.012					.012		TiO_2 . . 1.36	.016	TiO_2 . . 1.29	.015
MnO . . .52	.007							MnO . . .87	.012	MnO . . .22	.003
CaO . . 11.40	.203			.130	.073			CaO . . 14.11	.251	CaO . . 22.76	.406
MgO . . 8.32	.208				.073		.135	MgO . . 6.96	.174	MgO . . 2.70	.067
Na_2O . . 1.93	.031		.031					Na_2O . . 1.29	.020	Na_2O . . .54	.008
K_2O . . .14	.001	.001						K_2O . . 1.39	.014	K_2O . . .04	.0004
H_2O . . 2.73	.151						.151 ?	H_2O . . 6.48	.360	H_2O . . 3.56	.197
Specific gravity 2.69. Augite taken as $\dot{Mg} : \dot{Ca} : \dot{Fe} = 3 : 3 : 1$.								Specific gravity 2.85.			

On the Mesnard property, fifty feet west of the Houghton Conglomerate, there is a pseudo-amygdaloid melaphyre, which I mention here, because the changes that have taken place in it belong more properly in the stage of development found most commonly among the amygdaloids.

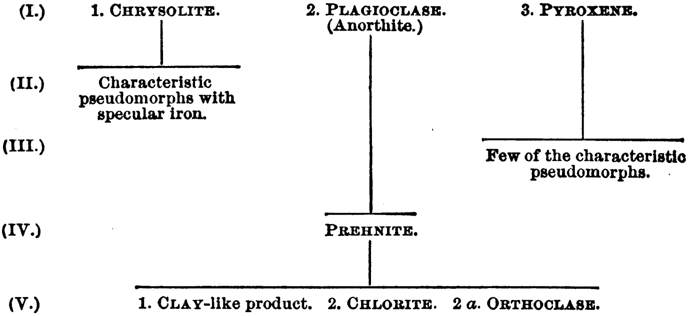
In a fine-grained, greenish-brown matrix lie pseudo-amygdules, which sometimes attain a diameter of one inch or more. On breaking these, we find a soft, dark-green compact substance, speckled with white and red, the latter from orthoclase, which, in places, shows the combination of a prism with the basal plane.

In thin sections, the matrix is found to be of the same type as the "greenstone," though coarser grained, and less unaltered. Here, as there, the chrysolite grains are crowded into the spaces intervening between relatively large areas, each of which consists of a pyroxene individual, enclosing many plagioclase crystals. The constituents are plagioclase crystals, generally very fresh, much unaltered pyroxene, and relatively few of the characteristic pseudomorphs after this, but many after chrysolite, associated with considerable specular iron, also from the chrysolite in part. Besides these, there are numerous pseudo-amygdules of chlorite and some pseudomorphs of chlorite after plagioclase. Optical measurements in the zone $O : i\bar{i}$, appear to indicate anorthite.

The large pseudo-amygdules were undoubtedly once prehnite; but of this there now remain three products. Rounded areas of a soft, opalescent, white, translucent substance show a minutely scaly aggregate polarization, and revolve equally bright, without apparent change, between crossed and parallel nicols: this is probably a clay. These areas are fringed with a hard, white, or pink-white mineral, showing granular aggregate polarization, and belonging to the orthoclase. Often this feldspar occupies a large part of the white areas, and is then distinguished from the soft substance by its coarse aggregate polarization of light. These areas of soft, white substance and orthoclase are surrounded by a green chloritic mineral, which is made up of minute spheres with radiating structure, and which resembles that of the smaller pseudo-amygdules in the matrix.

The appearance of the sections is such, that the soft, white alteration product of the prehnite seems to be the starting-point for the formation of both the orthoclase and the chlorite.

Paragenesis: —


(I.)
1. Chrysolite.
2. Plagioclase. (Anorthite.)
3. Pyroxene.
(II.)
Characteristic pseudomorphs with specular iron.
(III.)
Few of the characteristic pseudomorphs.
(IV.)
Prehnite.
(V.)
1. Clay-like product.
2. Chlorite.
2 a. Orthoclase.

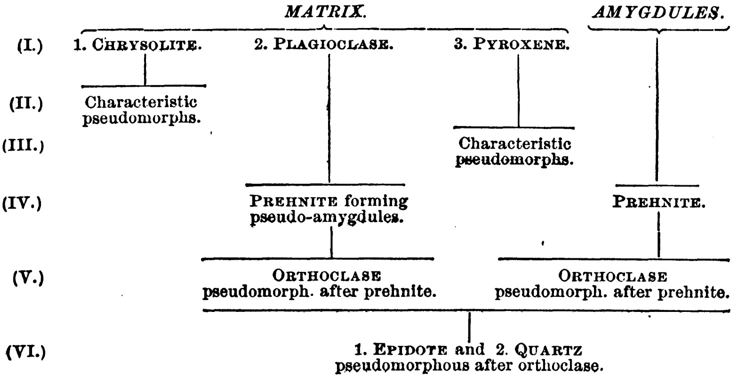
One hundred and fifty-eight feet west of the Isle Royale copper-bearing bed, on the Sheldon and Columbian property, there is a very interesting amygdaloid. It has an aphanitic, brownish-green matrix, abounding in amygdules of rather irregular shape, but with sharply defined contours. These vary from microscopic size to several inches, the larger ones having the most irregular forms. The larger ones consist of intimately associated white prehnite, granular red orthoclase, quartz and epidote. The smaller ones, containing little prehnite visible with the naked eye, have an outer member of red orthoclase freely crystallized in the middle, and have in the centre, quartz, or epidote in small crystals, or both.

The feldspar crystals are profoundly altered, and present now mere honeycombed forms.

In thin sections, the orthoclase pseudomorphs after prehnite still polarize the light; but such of the feldspar substance as remains is rendered impellucid by many suspended particles of iron oxide; and the honeycomb cells are filled with quartz, which also occupies the central area of the amygdule. Epidote, in short and long prisms, occurs within the feldspar forms, and often starting in the cavernous interior projects beyond the end of a feldspar, and is there wholly enclosed in quartz; it also occurs apparently wholly suspended within quartz individuals.

In the matrix, relatively few of the plagioclase crystals show a just apparent twin-striation in polarized light. In most of them it has disappeared. There is no unaltered pyroxene, but there are some of the characteristic pseudomorphs after that mineral, and others after chrysolite. The interstitial spaces are filled with an iron-stained, soft, slightly green substance, somewhat resembling that of the pseudo-amygdules. Besides this, the matrix is in many places filled with pseudo-amygdules, — many wholly occupied by epidote aggregates, others by orthoclase with epidote. These appear to have formed at the cost of the plagioclase. Some of the plagioclase crystals, especially near these pseudo-amygdules, are partially changed to aggregates of epidote.

Paragenesis: —


MATRIX.
AMYGDULES.
(I.)
1. CHRYSOLITE.
2. PLAGIOCLASE.
3. PYROXENE.
(II.)
Characteristic pseudomorphs.
(III.)
Characteristic pseudomorphs.
(IV.)
PREHNITE forming pseudo-amygdules.
PREHNITE.
(V.)
ORTHOCLASE pseudomorph. after prehnite.
ORTHOCLASE pseudomorph. after prehnite.
(VI.)
1. EPIDOTE and 2. QUARTZ pseudomorphous after orthoclase.

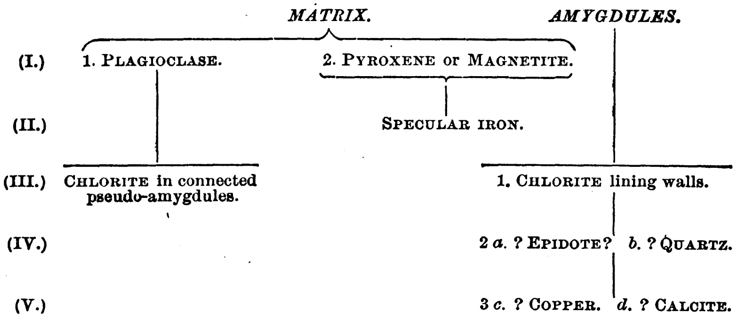
Spike Amygdules. — I have before me a specimen from one of the mines working in an amygdaloid. It has an even purple-brown matrix, in which occur isolated porphyritic crystals of red feldspar sometimes $\frac{1}{10}$ inch in size. Some of these may be orthoclase, as they show no twin striation on the cleavage planes in reflected light, while others are evidently triclinic. The loupe discovers numerous minute flakes of specular iron. Besides these, there are many very small round amygdules of chlorite, each forming a sphere with radiating structure, while others, always larger ones, have an outer ring of this chlorite, and a central filling of calcite, in which the uninterrupted cleavage indicates a single individual. The rock contained, also, many irregularly cylindrical cavities, often 5 inches long, and $\frac{1}{10}$ to $\frac{1}{3}$ inch thick, running parallel to each other and perpendicular to the plane of bedding. These are now filled chiefly with metallic copper, in continuous, more or less solid masses, which break out from the rock in the form of rough-sided spikes. Many of the small, round cavities adjoining a long one are connected with it and filled with copper, so that, when the large spike is detached, its sides have numerous small copper amygdules joined to it by a neck.

Besides the copper, these cavities contain quartz, calcite, and chlorite. The chlorite forms the oldest member, lining the walls of the former cavity; quartz, more or less massive, with frequent perfect prisms, comes next. Younger than the quartz are copper and calcite. The large calcite individuals break out with perfect casts of the quartz prisms, and the copper spikes are indented on the sides with impressions of the quartz crystals, showing every detail, including the horizontal striation of the prisms, with all the sharpness of an electrotype. The relative ages of the copper and calcite does not appear. Both the copper and calcite form fine seams, traversing the matrix; but they were not observed together in the same crack; and copper flakes abound in the cleavage of the macroscopic feldspar crystals.

On the sides of the spike-cavities, after removing the copper, were found groups of very small, hard, green crystals, which seem to be epidote. They are younger than the chlorite, and older than the copper; for this bears sharp impressions of the crystal groups.

In thin sections of the matrix we find the isolated macroscopic crystals of plagioclase, and more rarely others, which show no twinning, and are perhaps orthoclase; and these are undoubtedly primary constituents. Aside from these, the matrix consists of small plagioclase crystals, more or less altered, but generally showing the twinning in polarized light, and lying in an almost continuously connected mass of pseudo-amygdaloid chlorite, which is frequently obscured by aggregated flakes of specular iron and brown stains.

Paragenesis: —

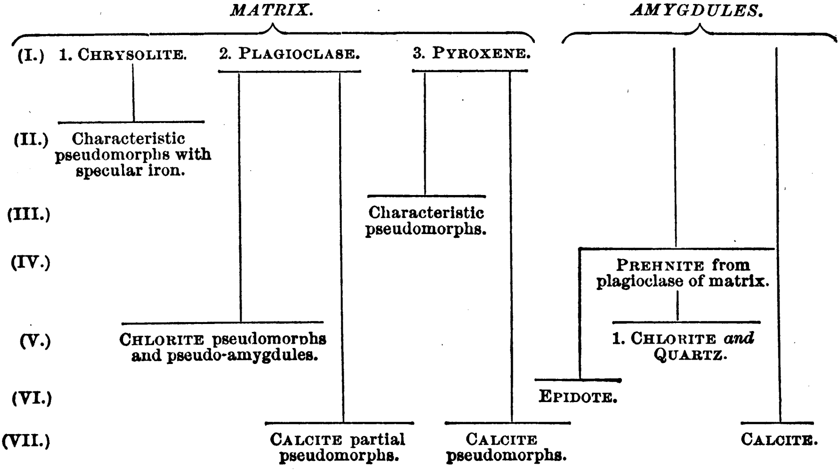


A purple-brown amygdaloid from the Sheldon and Columbian property has a very fine-grained matrix. It contains, 1st, spherical amygdules, ⅓ to ½ inch in size, of prehnite, more or less altered to a pliable, white, chalky substance; 2d, spherical amygdules, ⅓ inch and less, of dark, green chlorite, with finely scaly texture, enclosing a little quartz; 3d, spherical amygdules, with a central filling of the white altered prehnite, of very irregular shape, and surrounded by epidote, with comparatively coarse crystallization, and seemingly pseudomorphous after prehnite; 4th, an amygdule of epidote, containing two irregular central masses of calcite separated by a partition of epidote: the calcite adapts itself to the surfaces of the freely crystallized faces of the epidote crystals; 5th, amygdules filled with epidote alone in crystalline masses radiating from several circumferential points into the interior.

In thin sections of the matrix, the plagioclase crystals retain, in many instances, tolerably defined twin striation in polarized light; but nearly all of them are partially, others wholly, changed to chlorite, which forms connected pseudo-amygdules throughout the matrix. Numerous characteristic pseudomorphs, with specular iron, after chrysolite occur. But with the exception of some characteristic pseudomorphs, all the pyroxene is now represented by calcite pseudomorphs, each showing *integral* polarization. Some of the plagioclase crystals seem, also, partly altered to calcite with aggregate polarization. The change from pyroxene to calcite was apparently here, as in the melaphyre out of Mabb's vein, the last transformation.

If we consider the prehnite to be the oldest member of the amygdules, as we have heretofore found it to be, and assign its age to the period of formation of the pseudo-amygdules out of the plagioclase, we shall be justified in considering the chlorite and quartz amygdules as produced before the formation of the calcite pseudomorphs after pyroxene. For we have seen the change of prehnite amygdules to chlorite and quartz, where the pyroxene of the matrix was almost intact. The pseudomorphs of epidote after prehnite were probably mediated by the infiltration of the dissolved products of alteration of the pyroxene.

If this interpretation be right, the paragenetic tree should be: —


MATRIX.
AMYGDULES.
(I.) 1. CHRYSOLITE.
2. PLAGIOCLASE.
3. PYROXENE.
(II.) Characteristic pseudomorphs with specular iron.
(III.) Characteristic pseudomorphs.
(IV.) PREHNITE from plagioclase of matrix.
(V.) CHLORITE pseudomorphs and pseudo-amygdules.
1. CHLORITE *and* QUARTZ.
(VI.) EPIDOTE.
(VII.) CALCITE partial pseudomorphs.
CALCITE pseudomorphs.
CALCITE.

Ossipee Amygdaloid. — A specimen from an amygdaloid, 725 feet east of the Calumet Conglomerate, on the Ossipee location, has a compact, amorphous-looking, soft, dark-green, and brown matrix. It contains numerous very irregular spots and patches of prehnite, from the size of a pin-head to several inches. These are in places more or less altered — some wholly — to a light and dark-green, soft, chloritic substance, which has conchoidal fracture, and appears amorphous, even under a strong loupe. In some of the amygdules this chloritic product is associated with intermingled calcite; in others, with quartz. The larger patches of prehnite contain druses, some of which were formed by removal of prehnite substance, while others seem to represent former cavities, and are now lined ¼ inch thick with reniform prehnite, now much altered and easily scratched. These druses are half filled with small well-formed crystals of epidote and orthoclase, and isolated ones of copper. These sit upon the altered prehnite. The epidote, in minutely granular aggregates, penetrates the reniform masses of prehnite in such a manner as shows it to be pseudomorphous after the latter. The orthoclase crystals, in places, sit directly on the altered prehnite; in others, on the epidote crystals. The copper is also younger than the epidote. A thin section shows that the matrix has been prehnitized, while some of this prehnite is still present: a large part of it is changed to the pseudo-amygdaloidal chlorite, still preserving the plagioclase outlines.

A small specimen from an unknown locality in Ontonagon County, has a very soft purple matrix, which is impregnated with aggregates and crystals of epidote. It contains also irregular druses, lined with small epidote crystals, on which sit crystals of copper; and on these again, as well as on the epidote, crystals of orthoclase.

Bunches of minute, light, gray-green prisms of a very soft mineral sit on the epidote crystals. In so far as external appearance and all the optical tests that can be applied under the microscope go, this mineral is identical with that which, alone and included in quartz, forms amygdules in the cupriferous amygdaloid of the Pewabic and other mines. That from the Pewabic mine was analyzed by Macfarlane,[*] with the following result: —

---

[*] Geol. of Canada, 1866, p. 153.

Silica	46.48
Alumina	17.71
Protoxide of Iron	21.17
Lime	9.89
Magnesia	trace
Alkalies by difference	1.97
Water	2.78
	100.00

Mr. Macfarlane says: "It fuses before the blowpipe to a black, slightly magnetic glass. On ignition it changes to a light yellow color, losing 0.4 per cent of its weight. It is decomposed by hydrochloric acid, and the resulting solution contains protoxide, as well as peroxide of iron." In the analysis the iron was calculated as protoxide, and the difference between it and peroxide put down as water.

It seems possible that, at least, much of the lime was due to intermingled calcite; for I found, under the microscope, calcite particles in the powder scraped carefully from the amygdules of the Pewabic occurrence.

Between crossed nicols this mineral appears to be orthorhombic; with one nicol it shows feeble dichroism. It is, probably, one of the many minerals for which we have as yet no better general name than green-earth.

There can be little doubt that here, as in the specimen from the Ossipee amygdaloid, the matrix has been prehnitized, and the prehnite changed to pseudo-amygdaloidal chlorite, while the prehnite of the amygdules, small and large, was changed to epidote and orthoclase.

Amygdaloid from Section 8, *Town.* 47, *Range* 45. — Some interesting specimens, illustrating the change of prehnite into epidote and orthoclase, were collected by me in the Southern Copper Range at 400 paces north of the east ¼ post of Section 8, Town. 47, Range North, 45 west, in the southern part of Ontonagon County. The rock is an amygdaloid with a fine grained gray-green matrix. It contains numerous small amygdules of compact dark-green pseudo-amygdaloidal chlorite, and many large spike amygdules sometimes two or three inches long, and ¼ inch or less in diameter. Some of these are filled wholly with epidote, others with epidote as the older, and quartz as the younger member. In some, one portion of the spike consists of epidote, while the rest is the same dark-green chlorite that forms the small amygdules. More rarely the larger amygdules consist of red orthoclase, generally with quartz as a younger member. None of the amygdules are drusy. The epidote is in massive acicular aggregates, its structure converging towards the centre. The orthoclase and quartz are in granular aggregates.

In a thin section of the matrix we see that the greater part of the plagioclase still shows the twin striation in polarized light. There is some unaltered pyroxene, but none of the characteristic pseudomorphs after this. The section contains some pseudo-amygdules of the characteristic chloritic mineral; and others formed of granular aggregates of epidote and quartz are very frequent. Many of the plagioclase crystals seem to be partially changed to epidote.

Although no prehnite was observed in these specimens, the whole mode of occurrence seems to point to an alteration of prehnite as the starting-point for the formation of these tertiary products.

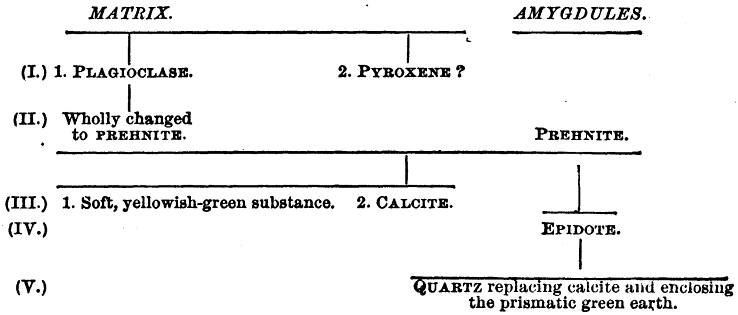
Paragenesis: 1. Pseudo-amygdaloidal chlorite; 2. Epidote and orthoclase; 3. Quartz.

Amygdaloid from Huron Mine. — In the copper-bearing amygdaloid beds of Portage Lake occur frequently considerable masses of amygdaloid, in which the matrix is a coarse, irregular patch-work of massive chloritic substance, of quartz, and of epidote. I have before me a specimen, six inches square, containing all these varieties. One end has a soft, dark-green, chloritic matrix, with large patches of prehnite, more or less altered to soft, light-green substance, and to calcite.

Thin sections show that the matrix has been wholly prehnitized. Fragments of prehnite remain throughout the matrix; but it is mostly changed to a soft, yellowish-green substance.

The amygdules, which were also of prehnite, are now, in places partly, in others wholly, changed. Many of the amygdules consist now partly of calcite, which, from the manner in which it encloses particles of prehnite, and of the soft, yellowish-green product of prehnite, is evidently pseudomorphous after it; the other portion of the same amygdule is often prehnite, more or less changed to a mass of prisms of a light-green substance, which form both on the outside and in the interior of the amygdules. These prisms are monoclinic, and are, probably, epidote. While the calcite encloses the yellowish-green alteration product, it does not contain this epidote-like substance. Where this is in contact with the calcite, the line of separation is sharply drawn. The calcite was formed contemporaneously with the yellowish-green product, or before it; it forms also veinlets through the matrix.

After part of the prehnite had been replaced by calcite, this form of change ended, and the remaining prehnite was subjected to a new process of alteration, — the change to the prismatic substance. In other amygdules a still later phase is apparent; here, after a part of the prehnite had been changed to the yellowish-green substance and calcite, and the rest to the soft, green, prismatic substance, the calcite was replaced by quartz. The quartz forms veinlets in the matrix, cutting those of calcite, while in the amygdules it encloses many fringed-edged fragments of calcite, and also the epidote product of prehnite. The quartz contains many fluid cavities, some with movable bubbles. None of the bubbles showed any change when heated to 100° C.


MATRIX.
AMYGDULES.
(I.)
1. PLAGIOCLASE.
2. PYROXENE ?
(II.)
Wholly changed to PREHNITE.
PREHNITE.
(III.)
1. Soft, yellowish-green substance.
2. CALCITE.
(IV.)
EPIDOTE.
(V.)
QUARTZ replacing calcite and enclosing the prismatic green earth.

The chloritic matrix passes gradually into the quartz matrix, which forms the middle zone of the specimen. This consists of purple-brown compact quartz, in which no crystal-faces occur. This portion breaks with sub-conchoidal fracture. It abounds in amygdules of white quartz and green epidote, the latter sometimes in crystals $\frac{1}{10}$ inch long, imbedded in quartz. The amygdules are, in places, half quartz and half calcite.

In thin sections the matrix shows the usual feldspar outlines, filled with a limpid colorless substance, and surrounded and sharply defined by a soft, impellucid, iron-stained substance. Some of the characteristic pseudomorphs after pyroxene also occur.

But in polarized light the bulk of the rock is seen to be quartz, with very coarse granular aggregate polarization, so coarse that each integral grain encloses and fills many feldspar outlines.

In parts of the sections this office is performed by prehnite in the same manner as by quartz. But this is evidently only a fragmentary residue. We have here on a large scale, in the whole matrix, what we saw in the other part of the specimen only in amygdules; here the formerly wholly prehnitized matrix has been almost entirely changed to quartz, perhaps after going through an intermediate change to calcite. Here, too, the quartz encloses large numbers of the delicate prisms of epidote-like substance.

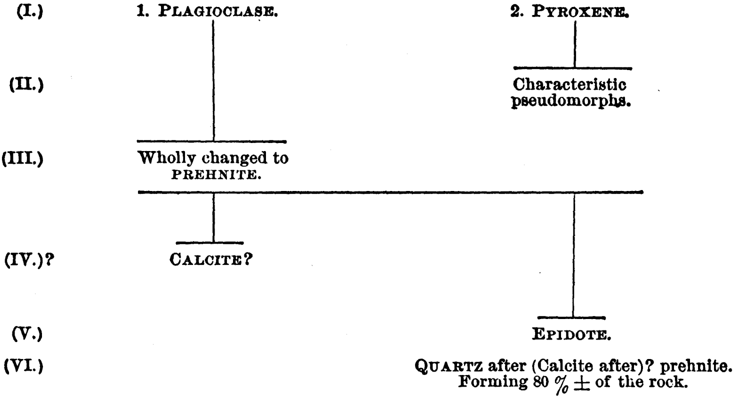
An analysis of this part of the specimen, by Mr. Geo. W. Hawes, gave, as a mean of two analyses, —

Silica	51.42.
Alumina	13.38.
Ferric oxide	9.59.

Ferrous oxide	2.45.
Manganous oxide	.48.
Lime	17.45.
Magnesia	2.14.
Soda	.19.
Water	1.13.
Titanic acid	1.72.
	99.91.

Free quartz, 10.86 per cent. Sp. gr. 3.45.

Metallic copper, 3.43 per cent. Sp. gr., calculated after deducting for quartz and copper, 3.32.


(I.)
1. PLAGIOCLASE.
2. PYROXENE.
(II.)
Characteristic pseudomorphs.
(III.)
Wholly changed to PREHNITE.
(IV.)?
CALCITE?
(V.)
EPIDOTE.
(VI.)
QUARTZ after (Calcite after)? prehnite. Forming 80 % ± of the rock.

The rest of the specimen is a very irregular mixture of the purple quartz matrix (with its quartz amygdules), and light-green epidote impregnated with rough threads of copper.

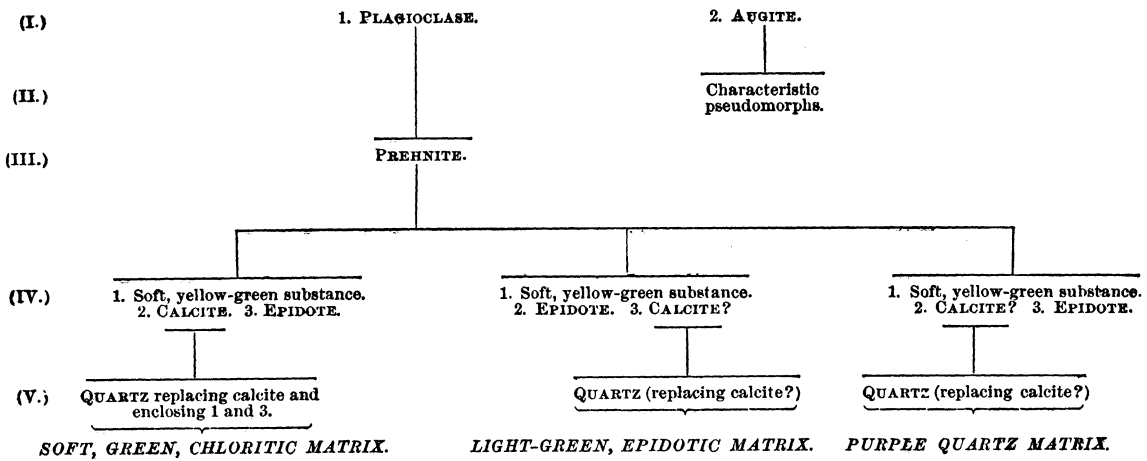
In thin sections it is found to consist of epidote, with more or less distinct crystal outlines, a soft, yellowish-green substance, and quartz which encloses the two other constituents, and permeates the mass in such a manner as to make it evident that it has replaced some preexisting substance — calcite? — in which the epidote and green substance lay.

That the quartz is younger than the epidote is shown by the fact that crystals of this are included in integral quartz grains.

Paragenesis: —

Epidote
1. Soft, yellowish-green substance. 2. Quartz.

PARAGENESIS OF THE SPECIMEN AS A WHOLE.


(I.)
1. PLAGIOCLASE.
2. AUGITE.
(II.)
Characteristic pseudomorphs.
(III.)
PREHNITE.
(IV.)
1. Soft, yellow-green substance. 2. CALCITE. 3. EPIDOTE.
1. Soft, yellow-green substance. 2. EPIDOTE. 3. CALCITE?
1. Soft, yellow-green substance. 2. CALCITE? 3. EPIDOTE.
(V.)
QUARTZ replacing calcite and enclosing 1 and 3.
QUARTZ (replacing calcite?)
QUARTZ (replacing calcite?)
SOFT, GREEN, CHLORITIC MATRIX.
LIGHT-GREEN, EPIDOTIC MATRIX.
PURPLE QUARTZ MATRIX.

“*Epidote Lode.*” *Mesnard.* — Among the rocks resulting from the alteration of the amygdaloids is one which is generally called epidote, and which seems to have given its name to the “Epidote lode,” north of Portage Lake. It is a light-green, hard rock, with an amorphous-looking matrix, and containing amygdules and seams of quartz. Even the naked eye detects countless minute seams of quartz, which traverse the matrix in a manner that suggests the former existence of shrinkage-cracks. In thin sections this rock is seen to consist of bristling masses of a faintly green mineral, in long, thin prisms. These crystals, when seen in very thin parts of the section, under Hartnack's No. 7, and between crossed nicols, generally become dark when oblique to a nicol plane; but occasionally one is found in which the maximum extinction occurs when the longer direction of the prism is parallel to a nicol plane; it is, therefore, a monoclinic mineral.

These crystals are suspended in quartz, which forms a considerable percentage of the rock, not only as amygdules, but as veinlets and matrix.

The quartz is undoubtedly the younger mineral, and the appearance suggests that the rock has been an amygdaloid, of which the matrix was altered finally to this green mineral, and then impregnated with quartz. The resemblance to the Huron mine occurrence suggests that the matrix passed through the prehnite stage.

The absence of free iron-oxide in these epidote-quartz rocks can be explained only by supposing that it entered into combination to form the ferric silicate.

The following is the mean of two analyses made for me, by Mr. G. W. Hawes, in the Laboratory of the Sheffield Scientific School: —

SiO_2	58.87
Al_2O_3	13.05
Fe_2O_3	4.29
FeO	2.70
MnO	.20
CaO	14.88
MgO	1.60
K_2O	.06
Na_2O	.24
H_2O	4.38
	100.27

The free quartz was determined by M. Müller's method,* digesting the powder with phosphoric acid. The appearance under the microscope would suggest that much more of the silica should be credited to free quartz than the 10.89 per cent given by Müller's method. I should say that twenty-five to thirty per cent would be nearer the truth. The substance is, probably, quartz, and an epidote very poor in iron.

Sp. gr. 2.88. Free quartz, 10.89.

Sp. gr., after deducting the quartz, 2.91.

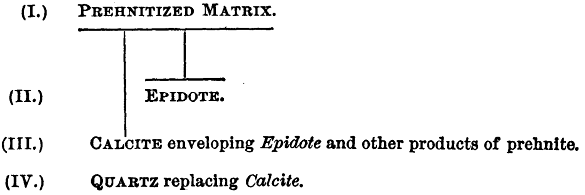
---

* Journ. f. pr. Chemie, xcv. 43, and xcviii. 14.

Epidotic Amygdaloid. — In the copper-bearing beds worked at Portage Lake, there occur frequently considerable masses of a hard, light-green, generally fine-grained, epidotic rock, which is often quite free from amygdules. Thin sections show that it consists of a granular aggregate of epidote and quartz, with metallic copper. In parts of the section, the epidote predominates, and the quartz is only just apparent. In other parts, the quartz is in the majority. The grains forming the quartz aggregate are small, and not detrital; they are united without interstices, and were undoubtedly crystallized in the positions they now occupy. The quartz also forms veins, cutting through the more epidotic portions, and throughout the sections it is clearly younger than the epidote; for grains and crystals of the latter are included in the interior of quartz individuals. It is evident that either the two minerals crystallized together, or that the epidote was originally held together by some substance which has been replaced by quartz. The observations on thin sections of the quartz-epidote rock from the Huron justify us in supposing that here, as there, the quartz has replaced some more soluble mineral. On one part of that specimen we saw remnants of prehnite, partially changed to calcite, and also half-finished pseudomorphs of quartz after the same calcite. In another part of that specimen the calcite was gone: but the quartz forming nearly all of the matrix enclosed the same alteration products of prehnite that we saw in the calcite in the other part; while in the epidotic part of the specimen we had simply epidote added as an older constituent, enveloped by quartz.

All my observations seem to indicate clearly, that the epidotic portions of the altered amygdaloids are a product of the alteration of prehnitized matrix.

Its paragenetic relations are, probably, nearly as follows: —



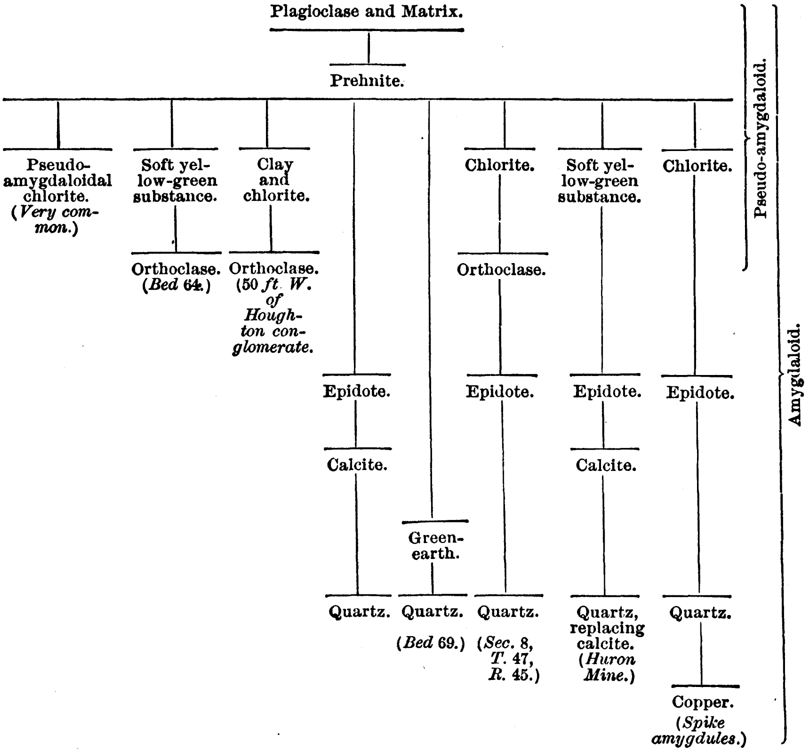
(I.) PREHNITIZED MATRIX.

(II.) EPIDOTE.

(III.) CALCITE enveloping *Epidote* and other products of prehnite.

(IV.) QUARTZ replacing *Calcite*.

I have attempted to correlate the typical ones among the different sets of paragenetic schemes in the annexed table, and to show, by this, which portions of the progressive changes caused the pseudo-amygdaloids or middle zone, and which the more highly altered forms of the amygdaloids proper: —


Plagioclase and Matrix.
Prehnite.
Pseudo-amygdaloidal chlorite. (Very common.)
Soft yellow-green substance.
Orthoclase. (Bed 64.)
Clay and chlorite.
Orthoclase. (50 ft. W. of Houghton conglomerate.)
Epidote.
Calcite.
Quartz.
Green-earth.
Quartz. (Bed 69.)
Chlorite.
Orthoclase.
Epidote.
Quartz. (Sec. 8, T. 47, R. 45.)
Soft yellow-green substance.
Epidote.
Calcite.
Quartz, replacing calcite. (Huron Mine.)
Chlorite.
Epidote.
Quartz.
Copper. (Spike amygdules.)
Pseudo-amygdaloid.
Amygdaloid.

With few exceptions, the course has been as follows: —

Pseudo-amygdaloid stage.

I. Hydration of *chrysolite*, when present.
II. Change of *augite*, loss of lime, and partial loss of iron and magnesia.
III. Change of *feldspar* to *prehnite*, and formation of *prehnite pseudo-amygdules*.
IV. Change of *prehnite* to *chlorite*.
IV *a*. Change of *prehnite* to *orthoclase*.

Amygdaloids.

I. Filling amygdaloidal cavities with *prehnite*, or other minerals. Change of *matrix* to *ferruginous prehnite*.
II. Change of the *prehnite*, in places, to *chlorite*; in others, to *calcite* and *green-earth*; in others, to *epidote* and *calcite*.
III. Entrance of *quartz*, filling all the interstices and replacing the *calcite*.

This is the broader history. Orthoclase is here, as in the pseudo-amygdaloid, of sporadic occurrence, and a product of the prehnite.

The changes under II. may affect only the amygdules, or, if the matrix was prehnitized, it applies to the whole mass of the amygdaloid. It does this in such a manner that, where carried to its extremes, considerable portions of the bed have lost every semblance of an amygdaloid, and consist now of chlorite, epidote, calcite, and quartz, more or less intimately associated, or forming larger masses, of the most indefinite shapes, and merging into each other. Sometimes portions of partially altered prehnite occur. In places, considerable masses of rich brown, and green fresh prehnite filled with copper occur; but, as a rule, this mineral has given way to its products.

To this process, the copper-bearing beds of Portage Lake — wrongly called lodes — owe their origin. Considerable portions of these beds are but partially altered amygdaloids, containing amygdules of prehnite, chlorite, calcite, or quartz, with more or less copper; other portions are in the condition described above.

This, too, (II. and III.), appears to have been the principal period of concentration of the copper. In the still amygdaloidal portions, this metal was deposited in the cavities and in cleavage-planes of some minerals, and replaced calcite amygdules, &c. But in the confused and highly altered parts of the bed it crystallized free, where it had a chance: more generally it replaced other minerals on a considerable scale. It formed, in calcite bodies, those irregular, solid, branching forms, that are locally known as horn-copper, often many hundred pounds in weight; in the epidote, quartz, and prehnite bodies, it occurs as thread and flake-like impregnations; in the foliaceous lenticular chloritic bodies, it formed flakes between the cleavage planes and oblique joints, or in places — and this is more particularly true of the fissure-veins, which we are not now considering — it replaces the chloritic, selvage-like substance till it forms literally pseudomorphs, sometimes several hundred tons in weight.

When the amygdaloid has arrived at the condition we have been describing, it assumes some of the characters of a vein, in that, although it presents no open fissure, it contains greater or smaller masses of calcite and other minerals that are easily replaced by an intruder. To this period, probably, belongs the replacement of calcite by datolite; and here, also, the rather rare occurrence of analcite crystals, and the pseudomorphs of orthoclase after these.

As I have already remarked, the pseudo-amygdaloids are merely altered forms of the same rock as the lower zone. There seems to be a definite limit at which this progressive change stops, and that is when all the augite is changed to its green pseudomorph, and a large percentage of the rest of the rock consists of pseudo-amygdules of delessite, and partial pseudomorphs of this after plagioclase. The occurrence of epidote and quartz is not general, and is then confined to scattering pseudo-amygdules, in which these minerals have succeeded prehnite, perhaps in the local absence of the conditions necessary to produce the usual delessite.

Thus I conceive that the extent of the change to the pseudo-amygdaloidal form is conditioned essentially by the amount of augite present, to supply first the lime necessary to aid in changing the plagioclase to prehnite, and next the iron and magnesia to form the delessite, whether by acting directly on the feldspar substance or on the prehnite.

The amygdaloïds proper were, probably, both structurally and chemically, somewhat different from the lower zone, in that it is reasonable to suppose that, in addition to being more or less porous, they contained a greater or less amount of amorphous base, which is more easily altered than a crystalline aggregate. But, from whatever cause, the amygdaloids have, as we have seen, been capable of much greater changes than the lower zone: in them the tendency is undoubtedly towards the formation of quartz, chlorite, and epidote rocks as a more stable limit, through the mediation of prehnite and calcite.

There is one form of change in some amygdaloids that I have not mentioned; namely, the laumontitic. I have not had sufficiently good material to work upon, and have not studied it to any extent under the microscope. Wherever I have been able to determine its relative age, as compared with prehnite, I have found it to be older than the latter. The macroscopic appearance of some beds of this amygdaloid suggest, that they have not only had the cavities filled with laumontite, but that the matrix has been more or less changed to the same zeolite.